Acoustic Features of the Vocalisations of Two Children Pre- and Post-Cochlear Implantation:

The Effects of Auditory Feedback

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Master of Audiology

By Simone Coyle

Department of Communication Disorders

University of Canterbury

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Abstract

The present study investigates acoustic changes to the voices of two congenitally deaf toddlers before, during, and after activation of cochlear implants (CIs). Vocal segment duration, fundamental frequency (f0), and noise index (NI) were measured from weekly recordings spanning the months immediately preceding and following implant activation. Contrary to expectations, vocal duration and f0 increased for both children in the post-activation period; NI increased for one child and decreased for the other. These findings illustrate how the restoration of auditory feedback can affect the voices of preverbal deaf infants in ways largely unobserved in older children and adult implantees. This may be due to the commencement of a developmental stage of pre-babble vocal exploration. Nevertheless, these observable effects highlight the significant role auditory feedback plays in speech development.

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Lastly, thank you to my family - for reasons too numerous to list. I love you.

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List of Abbreviations

ABR	Auditory brainstem response
CDAP	Cask Data Application Platform
CI	Cochlear implant
DAF	Delayed auditory feedback
dB	decibels
dB HL	decibels Hearing Level
DIVA	Directions In Velocities of Articulators
EHDI	Early Hearing Detection and Intervention
ENT	Ear, Nose and Throat
f0	fundamental frequency
FDA	Food and Drug Administration
fMRI	functional Magnetic Resonance Imaging
HA	Hearing aid
HI	Hearing impaired

HNR	Harmonics to noise ratio
Hz	Hertz
Md	Median
MDVP	Multidimensional Voice Program
ms	Milliseconds
NH	Normal hearing
NHR	Noise to harmonics ratio
NI	Noise index
OAE	Oto-acoustic emissions
PET	Positron Emission Tomography
s	Seconds
SD	Standard Deviation
TAF	Transformed auditory feedback
USA	United States of America
WAV	Waveform Audio File Format

1 Literature Review

1.1 Introduction

This literature review aims to investigate the effects of restored auditory feedback on the vocal parameters of paediatric cochlear implantees. The literature on vocal analysis of cochlear implantees has largely focused on adults and older children, whilst the evidence regarding infants is neither complete nor consistent. First, the design and purpose of cochlear implants is summarised. Second, the concept of auditory feedback is introduced and elaborated upon in terms of current models of speech production. This is related back to the importance of auditory feedback access for infant speech development. Of course, anatomical development plays a role in speech development as well, and these factors are highlighted. Next, the benefits of exploring the vocal development of hearing impaired infants through rehabilitation processes are explored, and the arguments for early cochlear implantation are noted. Acoustic parameters of infant voice are addressed, in terms of the literature on both normal hearing and hearing impaired infants. This review is limited to literature including the vocal parameters fundamental frequency, vocal duration, and noise proportions. Findings on the effects of infant cochlear implantation with regards to these vocal parameters are highlighted, and finally conclusions are drawn to note the limitations of these studies. From this conclusion, a current research question is produced and hypotheses are drawn regarding the available vocal data of two infants undergoing cochlear implantation.

1.1.1 Terminology. It is firstly necessary to clarify some broad terms used in this literature review (and the following thesis). In general development terms, ‘baby’ describes a young child from birth to four years old; ‘infant’ describes a baby in the first year of life, and ‘toddler’ describes a baby from one year to four years old. However the terms are used somewhat interchangeably in the literature, particularly when referring to children who progress from the first year to the second year of life during longitudinal analyses. As this thesis explores the vocal analysis of two toddlers who are at speech development stages of an infant, the swapping between terms is sometimes necessary; however accurate descriptors have been used where possible.

There are also various terms to describe people with hearing loss, such as deaf, Deaf, hard of hearing, and hearing impaired. (Luey, Glass, & Elliott, 1995). Deaf written with a capital 'd' generally represents individuals who identify with the Deaf community and Deaf culture. The children in this report are too young to identify with a culture and so this term has not been used. Hard of hearing often refers to people who communicate via speech and have anywhere from a mild to severe hearing loss. Again, this term is used infrequently with preverbal and congenitally deaf children. The term 'hearing impaired' has been a popular phrase in the past but is now becoming less commonplace. However this expression is still regularly referred to in literature, and so has been used here when the original report has also done so. Lastly, 'deaf' with a lower case 'd' generally describes someone with a severe to profound hearing loss, who largely communicates with hearing people (using speech) and associates with the hearing culture (Luey et al., 1995). The cochlear implanted children referred to in this literature review are generally born to hearing parents, and also present with very severe to profound hearing losses. Therefore the terms 'deaf' and 'hearing impaired' are used interchangeably to describe them.

1.2 Cochlear Implants: History and Design

The development of cochlear implants (CIs) has revolutionised the rehabilitation of adults and children with severe to profound hearing losses, allowing access to sounds they are otherwise unable to perceive. These are medical prosthesis devices, consisting of an electrode array which is implanted into the cochlea and connected to a receiver sitting under the skin of the temporal bone of the skull (Patrick & Clark, 1991; Wilson & Dorman, 2008). As shown in Figure 1.1, a speech processor (microphone) is worn behind the ear and electromagnetically transmits sounds to the receiver, which transforms the information into an electrical signal that is used to stimulate the corresponding areas of the auditory nerve. CIs therefore function to improve the hearing abilities of individuals with severe sensorineural losses, as they allow auditory information to bypass any cochlear and inner ear damage.

Swedish neurosurgeon Lundberg was the first to discover that direct stimulation of the auditory nerve gives the recipient a perception of noise, and in 1957 two French scientists made history by implanting an early version of the CI into a patient (Wilson & Dorman, 2008). By the 1980's the first single-channel implants were clinically introduced, with multi-channel implants following soon after. The Nucleus Mini22 was the first multi-channel CI approved for adult and child by the FDA in the late 1980s, as it was the first CI that was physically small enough to accommodate smaller head size (Patrick & Clark, 1991). In the subsequent decades rapid advancements in technology, research, and development have led to the introduction of cochlear implants with complex speech processing abilities, allowing patients to not just perceive environmental sounds but also effectively communicate via spoken language (Balkany et al., 2002; Clark, 2009). This is primarily achieved by allowing the CI wearer to gain access to audition, and auditory feedback information.

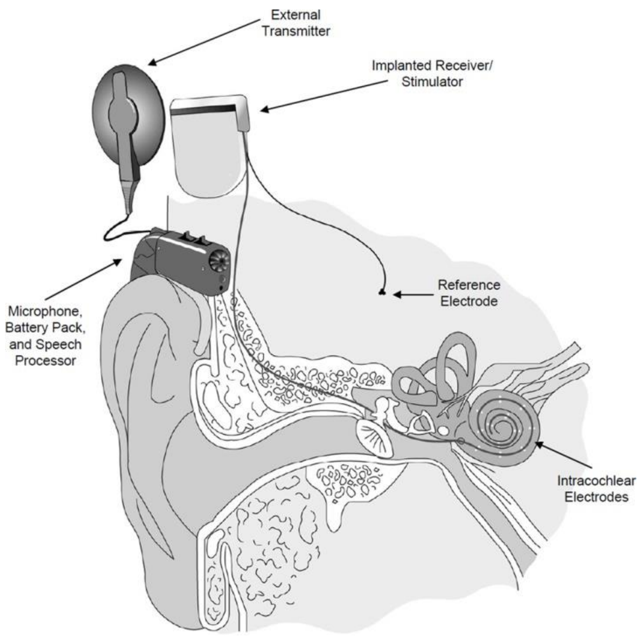

Figure 1.1: The multiple parts of a cochlear implant. External components pick up sound (speech) information and transmit this to the implanted components, which electrically stimulate the auditory nerve. Reprinted from Wilson and Dorman (2008, p. 34)

1.3 Auditory Feedback and Speech Production

Auditory feedback describes one of the mechanisms by which an individual moderates his or her own voice. The phenomenon was first investigated by Lee (1950a,), who found that playing a delayed version of a person’s own voice could cause the subject to develop a stutter, raise the pitch or amplitude of their voice, and slow their speaking rate. The effects of time-delayed auditory feedback (DAF) on speech production continued to be investigated into the following decades, with particular emphasis on the technique’s ability to treat speech disorders such as stuttering (Borsel, Reunes, & Bergh, 2003; Fairbanks & Guttman, 1958; Yates, 1963). Some researchers have however argued that favourable outcomes are not consistently observed, and may be merely due to the reduction of speaking rate which can be produced in other ways, invalidating the need for DAF treatment options

(Andrade & Juste, 2011; Ingham, 1993). As DAF became well-researched, so did the vocal response of pitch-transformed auditory feedback (TAF). Multiple studies have confirmed the parallel change to a speaker's pitch in response to an increase or decrease of the feedback's pitch (Burnett, Senner, & Larson, 1997; Larson, Burnett, Kiran, & Hain, 2000).

More recently, functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) technologies have allowed for the investigation of neural areas implicated in auditory feedback control. Tourville, Reilly, and Guenther (2008) demonstrated the activation of a neural pathway between auditory error cells in the somatosensory cortex (temporo-parietal region) and corrective articulator motor areas in the frontal lobes in response to pitch-shifted auditory feedback. Error cells are auditory neurons which detect mismatches between the expected outgoing auditory signal and the consequent incoming signal. The resulting activation of speech motor cells indicates the presence of corrective activations which send commands to the speech articulators following this mismatch. Comparable studies by Toyomura et al. (2007) and Parkinson et al. (2012) found similar pathways of activation, again with TAF. The former concluded that feedback control of pitch is dominated by the right hemisphere whilst the latter provided further evidence of the role of auditory error cells. Yet more analyses have demonstrated activation of these error cells by DAF, an effect not seen with normal rate, non-delayed feedback (Hashimoto & Sakai, 2003; Takaso, Eisner, Wise, & Scott, 2010). As Tourville et al. (2008) describe, these findings support the DIVA model of speech production.

1.4 The DIVA Model of Speech Production

The DIVA model (Directions into Velocities of Articulators), gives a theoretical, computer-based framework describing how auditory-related information is processed and speech movements are produced in the brain. In essence, DIVA proposes that speech motor commands are controlled by sound map cells which are in turn activated by either feedforward or feedback control subsystems (Guenther & Hickok, 2015). Feedback is divided into two types, known as the auditory feedback control subsystem (neural pathways providing the sound map cells with information on what the subject hears) and the somatosensory feedback control subsystem (providing kinaesthetic and proprioceptive information on speech articulators/the vocal tract) (Guenther, 2006). The feedback subsystems therefore facilitate comparisons between output and input signals, whilst the feedforward system sends action commands directly from the premotor and primary motor cortices, as illustrated by Figure 1.2.

The DIVA model is regarded as flexible, and is periodically modified to incorporate the findings of new research. The first version was proposed in the 1990s and updated editions have been published as recently as 2012 (Guenther, 1994, 1995a, 1995b; Guenther & Vladusich, 2012; Tourville & Guenther, 2011). Early versions theorised that this neural network is strengthened during a stage equivalent to babbling in infant speech development, when efferent motor outputs are compared back to the feedback subsystem inputs in a reverse-feedback manner (Guenther, 1995a). Feedback (both auditory and somatosensory) therefore plays a crucial role in developing highly accurate control over the speech system, allowing for effective error correction once the system has finished developing. After this learning phase the feedback subsystems undertake a lesser role in speech production, with accurate vocalisations able to be achieved using only feedforward commands. The role of auditory feedback is then to send inhibitory signals from speech sound map cells to the auditory error cells, unless (as described above in TAF and DAF studies) sound map cells sense a difference between the target speech sound and auditory feedback. Signal mismatches disinhibit the auditory error cells to provide corrective signals to the articulators (Guenther, 2006). It is in this way that individuals who acquire a significant postlingual hearing loss are still able to produce intelligible speech (albeit with some deviations) after many years of limited auditory feedback (Perkell et al., 1997).

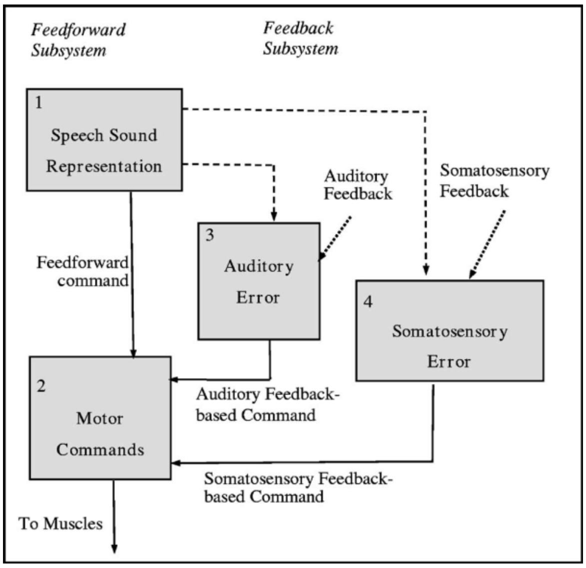

Figure 1.2. A simple schematic of the DIVA model of speech production. Cortical neurons are represented by boxes. Dashed lines represent the path of expected sensory signals (projections from the premotor to sensory cortices), dotted lines show afferent information projecting to the sensory cortex, and solid lines indicate efferent information which controls motor movements. Reprinted from Lane et al. (2005, p. 1638)

1.4.1 Alternatives to the DIVA model. Although the DIVA model is advocated by many researchers, some propose variations on these mechanisms of speech production. For example, forward models of speech production are commonly supported, with one such concept suggested by Larson, Altman, Liu, and Hain (2008). Larson et al. compare their model to Guenther and colleague's DIVA by noting the nonlinearity and complexity of networks proposed in DIVA compared to the linear concepts of f0 control in the forward-model. Hickok, Houde, and Rong (2011) built upon Larson and colleague's notions but give more emphasis to the feedforward subsystems, particularly in regards to activation of the error cells. Parkinson et al. (2012) highlighted the shortcomings of the DIVA model by assessing how it is interpreted. They argued that the DIVA model aims to conceptualise the control of vocalisation and phonation – i.e. the voice itself – whereas the control of speech is likely to require feedback of a greater degree and complexity than this model is able to represent.

Fundamentally however, all models share the same principal characteristics – a combination of (auditory and kinaesthetic) feedback and sensorimotor feedforward pathways. The growing literature and evidence base appears to only be increasing the similarities between the models. This is demonstrated by the addition of a kinaesthetic feedback loop to the forward model by Larson et al. (2008), just as is described in the DIVA model (Tourville et al., 2008).

1.5 Auditory Feedback and Hearing Impaired Infants

With these models in mind, the importance of auditory feedback in speech development is clear. Early studies using delayed auditory feedback on newborn cries discovered that cry duration decreased with increased DAF (Cullen, Fargo, Chase, & Baker, 1968). In contrast, the duration of words for children over the age of two years increased with DAF (Siegel, Fehst, Garber, & Pick, 1980). Further analyses indicated that the effect for children over two years was consistent, but not for those younger (Belmore, Kewley-Port, Mobley, & Goodman, 1973). This suggested that auditory feedback may play a different role in speech control after the acquirement of language, compared to pre-speech development.

Research has shown that hearing impairment does not largely affect the development of preverbal vocalisations in the first year of life, before the babbling stage (Scheiner, Hammerschmidt, Jürgens, & Zwirner, 2004, 2006). One study of preverbal vocalisations found that the amount and structure of simple single noncry vocalisations produced was unaffected by hearing ability, whilst vocal sequences (i.e. babbling) were significantly less frequent overall for hearing impaired (HI) infants when compared to those with normal hearing (NH) (Scheiner et al., 2006). Although severely hearing impaired infants may be provided with hearing aids at an early age, the development of babbling is often much later than normal hearing infants – if it develops at all (Iyer & Oller, 2008; Scheiner et al., 2004). This indicates the great significance of sufficient auditory feedback in the development of speech, particularly in achieving the babbling stage at a normal developmental rate.

There is also evidence that cochlear implants provide restoration of auditory feedback. For example, cochlear implanted children appear to show similar responses to DAF as normal hearing children (Tye - Murray, 1992), as well as display faster development of babbling than unimplanted deaf children (Colletti et al., 2005; Schauwers, Gillis, Daemers, De Beukelaer, & Govaerts, 2004). Furthermore, studies on the rapid emergence of babbling after the acquirement of auditory feedback through CIs indicate that CIs are crucial aids to encourage infant vocal exploration and the subsequent development of babbling (Fagan, 2014, 2015).

1.6 Stages of Speech Development

Kent and Murray (1982) and Oller, Eilers, Neal, and Schwartz (1999) give concise overviews of the stages of infant phonation development over the first year of life. Kent and Murray (1982) reasoned that although disputes still arise on the identification and exact timing of these stages, the overall sequence of events was well-accepted worldwide (an example of which is shown in Figure 1.3). This notion still holds true today, with most researchers adopting a four- or five-stage model (Nathani, Ertmer, & Stark, 2006). In general, normal vocal development begins with a phonation stage, characterised by the production of quasivowels and glottal sounds which ends at about two months of age. This is followed by cooing, otherwise known as a primitive articulation stage when the infant first learns articulation movements. The cooing stage is characterised by an increase in the amount of vocalisations produced, as well as an increase in the variation of the sounds (Scheiner, Hammerschmidt, Jürgens, & Zwirner, 2002). Cooing develops into the expansion stage by eight months of age, when vowel and consonant sounds become more developed and begin to be used together (also known as vocal play). Vocal play also involves the introduction of new sounds to the infant's repertoire, such as squeals, growls, raspberries, yells, and more. This stage is when infants being to truly explore the types of vocalisations they are able to produce (Stark, 1981). Expansion leads towards babbling (reduplicated or canonical babbling) between five and ten months of age as the vowel and consonant sounds are combined in sequences to create syllables. Finally the infant produces protowords, followed by the first meaningful spoken words emerging around 10-18 months of age (Kuhl & Meltzoff, 1996).

As described by Oller et al. (1999), these speech studies do not generally include sounds which they term 'fixed vocal signals' (p. 225) such as laughs or cries, nor vegetative sounds. In the past these sounds have not been regarded as representative of speech and language development in the same way as nonfixed vocal signals, and are more often used to investigate topics relating to pathologies or the health status of infants (Chittora, 2016; Kheddache, 2015, Rothganger, 2003). Nevertheless, some studies have related cry development to that of speech and language (Fuamenya, Robb, & Wermke, 2015; Mampe, Friederici, Christophe, & Wermke, 2009).

Although it was initially thought that audition was not required to meet these milestones (Lenneberg, Rebelsky, & Nichols, 1965), as the aforementioned literature suggests, auditory feedback has been found to have a crucial effect on the timely development of speech and language (particularly from the babble stage onwards).

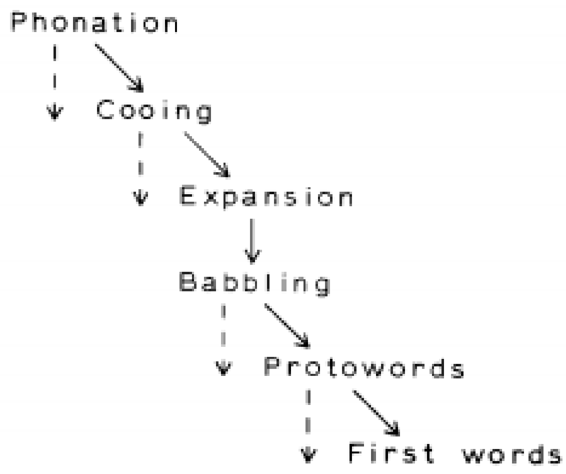

Figure 1.3. Stages of speech development in the first year of life, the dashed lines represent the possible retention of earlier vocal behaviours, even as the infant enters successive stages. Reprinted from Kent and Murray (1982, p. 361)

1.7 Anatomical Development of the Infant Vocal Tract

Infant vocalisation development is not just affected by input and output from the neural networks of speech production, but also by structural factors such as the anatomy and physiology of the respiratory system as well as that of the vocal tract itself. The vocal tract undergoes significant changes in the first few years of life and as the source-filter theory suggests, this influences the quality and development of speech (Fant, 1971). The vocal tract is comprised of oral and nasal cavities as well as the larynx (voice box) and pharynx (throat cavity). Cartilages of the larynx are moved by connecting muscles, which in turn change the length and tension of the vocal folds (mucous membranes stretched across the larynx) (Fant, 1971). When air is pushed from the lungs through the vocal tract and over the vocal folds which consequently vibrate, each cavity's variable shape changes the air flow's resonance, which influences the acoustic qualities of the vocalisation. Each cavity is smaller and shorter in infants, with the entire vocal tract lengthening more than twice over by adulthood at uneven rates between the structures (Vorperian et al., 2009). One such example is that the infant pharyngeal cavity is shorter with respect to the rest of the tract, but grows proportionately more during development (Kent & Murray, 1982). This lengthening decreases the frequency of the infant's vocalisations, as described by the acoustic theory (Fant, 1971). The angle of the oropharyngeal bend also changes, becoming almost 90° by adulthood (Mugitani & Hiroya, 2012). At around four to six months of age the infant's voice becomes more resonant due to changes in the velum and epiglottis (structures of the soft palate) which reduces the nasality of vocalisations (Sasaki, Levine, Laitman, & Crelin, 1977). These physical changes are collectively illustrated in Figure 1.4.

On a cellular level, the structure of paediatric vocal folds is also notably different to that of adults (Hartnick, Rehbar, & Prasad, 2005). In young infancy, this begins as a monolayer of cells and develops into a bilayer by around five months of age (Boseley & Hartnick, 2006). By the time a child reaches seven years old a third layer forms and the structure resembles fully developed adult vocal cords. The cricothyroid muscle of the larynx aids in the tension of the vocal folds and comprises a larger proportion of the laryngeal muscles in infants than in adults (Kahane & Kahn, 1984). Although gender differences exist in the structure of adult vocal tracts, these do not begin to appear until at least three years of age (Vorperian et al., 2011).

Of course, anatomical changes affecting the voice are not just limited to the vocal tract. Development of structures such as the lungs (and breathing processes) as well as reorganisation and myelination of the central nervous system also influence infant sound production. A more list of these factors is depicted in Figure 1.5.

Although anatomical maturation surely plays a role in the large variability and changes depicted in paediatric acoustic studies, Vorperian et al. (2009) note that most of the developmental changes have been attributed to increased speech motor and neuromuscular control (i.e. the refinement of the neural pathways noted in the DIVA model), rather than the sheer size and shape of the cavities.

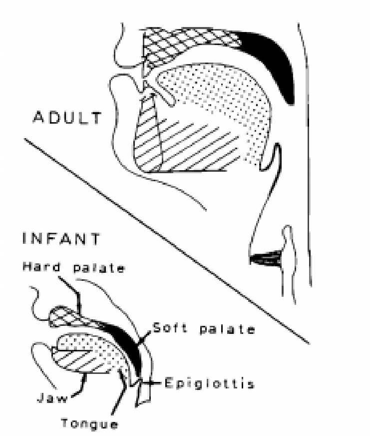

Figure 1.4. Anatomical differences between the infant and adult vocal tract. Reprinted from Kent and Murray (1982, p. 353)

TABLE 1. *Selected changes in factors that subserve breathing during the first year of life*

Changes in structure
Alveoli increase in number
Alveoli increase in size
Alveolar ducts increase in number
Alveolar surface area increases
Lung size and weight increases
Airways increase in radius and length
Changes in mechanics
Thoracic cavity enlarges and changes in shape
Inclination of ribs increases with upright posture
Chest wall compliance decreases with upright posture
Rib cage muscle bulk increases
Airway resistance decreases
Pleural pressure becomes more subatmospheric
Changes in functional behavior
Tidal volume increases
Expiratory reserve volume increases
Inspiratory capacity increases
Vital capacity increases
Progression from dynamic to passive end-expiratory level
Resting tidal breathing variability decreases
Respiratory rate decreases
Minute ventilation increases
Maximal inspiratory and expiratory pressures increase
Changes in ventilation, perfusion, and gas exchange
Pulmonary circulation develops
Pulmonary diffusion increases
Arterial oxygen tension increases
Maximal oxygen uptake increases
Changes in nervous system
Myelination of upper motoneuron tracts increases
Myelination of somatosensory pathways increases
Myelination of pre- and postthalamic proprioceptive pathways increases
Myelination of pre- and postthalamic exteroceptive pathways increases
Development of primary sensory and motor areas is completed
Development of secondary sensory and motor areas continues
Inputs and outputs from cerebellum increase

Figure 1.5. Anatomic and physiologic changes to the lungs and breathing system, which may play a role in infant vocal development. Reprinted from Boliek, Hixon, Watson, and Morgan (1996, p. 2)

1.8 Paediatric Auditory Studies: Early Implantation and Sensitive Periods

Although many studies attempt to make clarifications regarding the effect of deafness or auditory deprivation on infant development (and therefore, the converse process of auditory development with appropriate sensory stimulation), our current knowledge of auditory and speech development is still limited. This is in part due to ethical boundaries, as it is quite clearly inappropriate to intentionally deprive children of auditory stimulation for long periods of time. With that said, there is a population which possesses these characteristics naturally: prelingually deaf infants who are then fitted with CIs at a young age. These children provide a unique opportunity to observe the isolated effects of auditory feedback as it can be assumed that prior to implant activation, their access to audition is low. This assumption relates to a common candidacy criterion for infant cochlear implantation – individuals need to be confirmed to derive insufficient benefit from hearing aids for appropriate speech and language development, as evidenced by audiometric results or the absence of related developmental milestones (Bradham & Jones, 2008; Cohen, 2004; 2018).

Therefore even if hearing aids are worn prior to CI activation, the children's acquired auditory access from aids can be deemed small, supported by literature reviews which show deaf children gain more speech and language benefit from CIs than HAs (Bittencourt, Torre, Bento, Tsuji, & Brito, 2012; Bond et al., 2009). With this in mind, the activation of cochlear implants is most often considered the key event in restoring audition, and most studies on the effects of auditory feedback in cochlear implantation do not consider the prior wearing of aids at all.

At present, the FDA in the United States (and many other countries) approve cochlear implantation for infants over 12 months of age, although evidence is quickly growing that even earlier implantation can provide faster and greater speech and language benefits with little additional medical risks (James & Papsin, 2004; Nicholas & Geers, 2013; O'Connell, Holcomb, Morrison, Meyer, & White, 2016). This new knowledge is in line with the current treatment protocols for infants with all degrees of hearing loss, where early identification of hearing impairment and amplification provided before 6 months of age is well known to provide substantially better language outcomes (Yoshinaga-Itano, 2003; Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998). In 2007, Early Hearing Detection and Intervention (EHDI) guidelines were introduced in the United States by the Joint Committee on Infant Hearing, becoming the basis for many newborn hearing screening protocols (2007). In particular, the 1-3-6 EHDI guidelines state that all newborns should undergo a hearing screening before 1 month of age, follow-up evaluations for non-passed screenings by 3 months of age, and infants with confirmed hearing losses should be given appropriate intervention by 6 months of age. Yoshinaga-Itano and colleagues recently completed a follow-up study to her prominent 1998 work on the benefits of early intervention, which showed that adherence to these guidelines is successful in providing improved vocabulary outcomes (Yoshinaga-Itano, Sedey, Wiggin, & Chung, 2017).

With this research in mind, literature supports the benefits of early cochlear implantation, so long as it is medically appropriate to carry out the surgery. Extensive evidence shows that if auditory feedback is restored during the sensitive period of the auditory system (or as young as possible), (s)he is more likely to catch up to the developmental level of his/her normal hearing peers – particularly in regards to reaching the canonical babble stage (Colletti et al., 2005; Grant, Cheng, & Niparko, 1999; Sharma, Dorman, & Spahr, 2002; Sharma, Spahr, Dorman, & Todd, 2002). A sensitive period is the time frame in which a sensory system undergoes rapid neurological development, often occurring in infancy and young childhood (White, Hutka, Williams, & Moreno, 2013). Because cortical reorganisation, myelination, and neural synapse strengthening are occurring at an accelerated pace during this time, it is important for the system in question to be adequately stimulated in order for full functioning in the future. For the speech-motor system, this entails gaining access to a wide range of auditory and somatosensory sensations in order to develop vocal motor control, as well as speech and auditory processing abilities (Rauschecker, 1999). Early implantation therefore takes advantage of the neuroplasticity of young children in order to obtain speech and language outcomes that are more analogous to those of normal-hearing children, and is now supported by many medical professionals (Colletti et al., 2005; May-Mederake & Shehata-Dieler, 2013).

1.9 Acoustic Parameters of the Infant Voice

Many parameters have been used in the literature to assess speech development as well as differences between that of deaf and normal hearing children. This review has been refined to focus on three of these parameters: fundamental frequency, noise, and duration. Therefore the papers chosen here for review are those which are able to provide some information on these acoustic features. As these measures are usually taken to compare features pre- and post-intervention for HI children, most literature concerning infants with hearing loss has been included in the section on the effects of CI on voice.

1.9.1 Fundamental frequency: development in normal hearing infants.

Fundamental frequency (f0) describes the lowest frequency band found within a certain sound signal, and is analogous to the perception of pitch. According to the acoustic theory and source filter models of speech production, this characteristic is related to the laryngeal tone of the vocal tract; i.e. the taughtness of the vocal folds in response to the contraction of the laryngeal muscles (Fant, 1971). It is clear from the history of auditory feedback studies that control and development of f0 is somewhat dependent on auditory feedback, although anatomical changes to the vocal tract and vocal cords also play a role (Larson, 1998; Mugitani & Hiroya, 2012). In particular, the physical development between ages 2-3 years have been indicated in f0 values (Mugitani & Hiroya, 2012).

The changes to f0 during the development of normal-hearing infants have been well studied; however investigations have often focused on cries rather than noncry vocalisations – particularly for young infants (Daga & Panditrao, 2011; Esposito & Venuti, 2010; Wermke, Mende, Manfredi, & Bruscaglioni, 2002). Michelsson and Michelsson (1999) conducted a review of the literature and found young infant’s average cry f0 to be between 400-600Hz. Infant f0 is thought to generally decrease over time, although studies such as that by Gilbert and Robb (1996) show the opposite effect – a parallel increase in age and f0 that was suggested to be related to the development of intentionality within cries over the first year.

Young infant noncry data are less common in the literature, but a concise overview of created by Iyer and Oller (2008), and has been reproduced in Figure 1.6. This summary highlights the amount of variation that has been identified between each study (but also within each study; subject-to-subject and vocalisation-to-vocalisation). The noted papers investigated f0 of typically developing infants at varying ages until approximately 2 years of age. Mean f0 values were measured between 335 Hz by Laufer and Horii (1977) and 450 Hz by Kent and Murray (1982). As Iyer and Oller (2008) hypothesise, this may be due to both the age range of the studies but also the procedural methods undertaken, such as which vocalisations were included for analysis. These studies showed either a decrease or no change to mean f0 with an increase in age. Again, procedural variations such as the longitudinal nature of some studies were thought to affect whether f0 patterns were observed. Kent and Murray (1982) noted a particular decrease in f0 between six and nine months of age. The conclusions of the investigation by Iyer and Oller showed that age-matching deaf and normal hearing infants resulted in a significant difference between mean f0 values; however matching the groups by their stages of vocal development gave no statistically significant difference. As deaf infants are known to show slower vocal development than their NH peers, this analysis is of particular note.

Few noncry f0 analyses have been carried out since the Iyer and Oller review however some articles were excluded from their study, particularly those which did not provide the requisite values. For example, Fuller and Horii (1986) found the average f0 of vocalisations classed as ‘coos’ from 27 normal hearing 2-6 month olds to be 355Hz. Amano, Nakatani, and Kondo (2006) described that the mean vocal f0 decreased over the first five years of life of three children, but did not give f0 values.

Studies on F_0 in typically developing infants.

Study	Design	n	Ages	Mean F_0 (Hz)**	Range (Hz)	SD (Hz)
Delack and Fowlow (1978)	L	19 (10: 1 mo–1 yr; 9: ≤ 6 mo)	1 mo–1 yr (biweekly)	355	NA	NA
Kent and Murray (1982)	C–S	21	3, 6, 9 mos	3 mo: 445 6 mo: 450 9 mo: 415	350–500	NA
Laufer and Horii (1977)	L	4	1–24 wks (bimonthly)	335	317–342	utterance: 217–423
Robb and Saxman (1985)	C–S	14	11–25 mos	357	164–1366	session: 105 (45–238)
Robb, Saxman, and Grant (1989)	L	7	begin: 8–14 mo end: 19–26 mo	mono: 396 di: 399	mono: 289–642 di: 281–652	session: mono: 106 (23–307); di: 86 (18–202)
Sheppard and Lane (1968)	L	2	0–5 mos	429	384–481	utterance: ≤ 10% of mean F_0
Whalen, Levitt, Hsiao, and Somodinsky (1995)	L	12	6, 9, 12 mos	362	NA	NA

L= longitudinal; C–S= cross-sectional;

** mono= monosyllables; di= disyllables.

Figure 1.6. Noncry fundamental frequency studies on normal hearing infants. Reprinted from Iyer and Oller (2008, p. 918)

1.9.2 Fundamental frequency: development in hearing impaired infants. The literature on f0 for deaf infants is even less concise and more contradictory than that of normal hearing children. In general, HI infants produce vocalisations with a higher f0 and increased variability, however some may display the opposite pattern or no difference to NH infants at all (Iyer & Oller, 2008). Van Den Dikkenberg-Pot, Koopmans-van Beinum, and Clement (1998) provided an analysis which combined several previous papers on six deaf infants (and six age-matched, normal hearing peers) who were followed from 2.5 months until 18 months of age in total (Clement & Koopmans-van Beinum, 1995; Clement, Koopmans-van Beinum, & Pols, 1996). They found higher median f0 values for the deaf infants (average 368.5 Hz for deaf infants versus 354.9 Hz for normal hearing infants) until 13.5 months of age, but the difference was not statistically significant.

Studies of older children with hearing loss are generally less variable than their infant counterparts, showing more examples of atypical vocal profiles with high f0, although this is still far from consistent (Higgins, McCleary, Ide-Helvie, & Carney, 2005; Ryalls & Larouche, 1992).

From these studies, it can de determined that in normal hearing infants, f0 tends to decrease with age. Deaf infants generally exhibit f0 values that are higher or no different to that of normal hearing infants.

1.9.3 Vocal duration: development in normal hearing infants. Duration describes the length of vocalisations produced by an infant. Before the development of speech, this is usually measured by the onset and offset of voice during a single expiration (Fuamenya et al., 2015). Fuamenya et al. (2015) investigated the cries of 20 normal-hearing infants over the first three months of life. Cry duration showed a significant increase between months 1 and 2, which was sustained for month 3. The authors suggest this change may be due to the increase in respiratory lung volume at this age, as well as the increase in neurological control within the speech-motor system. Kent and Murray (1982) found the typical vocal duration of NH infants at 3,6, and 9 months of age to be less than 400ms, although histograms presented show the duration distributions to become more skewed to the right as the infants age. Robb and Saxman (1988) Kubaska and Keating (1981) investigated word duration in three NH infant's speech who were between 15 and 35 months old. Speech samples of word durations were taken every fortnight and showed that although some single words decreased in duration but the majority did not. The authors acknowledge that once a child is able to produce multiword utterances, the duration of nonfinal words appear to decrease. Robb and Tyler

(1995) found that the mean word duration of seven NH children aged between 8 and 26 months decreased, whilst the mean duration of nonword vocalisations (those which could not be likened to words by auditory analysis) did not change. Lyakso and Grigor'ev (2015) also found a decrease in duration of vowel-like utterances of 115 NH children between 3 and 9 months of age.

1.9.4 Vocal duration: development in hearing impaired infants The sequence of studies by Van Den Dikkenberg-Pot et al. (1998) on deaf infant speech development found interesting results in regards to duration: from 8.5-10.5 months of age, deaf infants begin to increase the duration of their vocalisations. This was hypothesised to be related to the relative complexity of the sounds, as they also noted changes to phonation. In contrast, infants with normal hearing displayed an increase in duration between 6.5-8.5 months as they entered the babbling phase, but then consistently exhibited a decrease in duration as they moved towards producing protowords and further speech development. These divergences lead to a statistically significant difference between the two groups from ages 10.5 months to 16.5 months. Again this was noted to be potentially related to the relative complexity of word production, compared to canonical babble. Over the 18 month period, the average duration of vocalisation by deaf infants was 996.7ms compared to 883.3ms for normal hearing infants.

Therefore, in general, deaf speakers tend to produce vocalisations, vowels and words of longer duration than normal-hearing speakers from the second half of the first year of life. This has been suggested to be an indication of the development of speech-motor skills, or the difficulty in perceiving (and producing) consonant sounds in the way NH infants are able to (Monsen, 1974). One study of 181 eight- and nine year old children who had been wearing a CI for at least four years showed that vowel and word durations were still unlikely to be close to that of normal hearing children (Uchanski & Geers, 2003).

1.9.5 Noise parameters: types of measures. Speech noise is described as segments of vocalisations which are aperiodic in nature, with irregular vibrations and no discernible pitch (f0). These characteristics arise when the vocal folds vibrate in an irregular manner (Buder, Chorna, Oller, & Robinson, 2008). The literature takes note of several variations of noise measures, which are very similar but with some important points of difference. In general, all measures give an indication of the 'roughness' of a vocalisation.

The most commonly used measure is harmonics to noise ratio (HNR). This is calculated by measuring the total duration of harmonicity in the vocalisation, and dividing this by the duration of aperiodicity (Hocevar-Boltezar et al., 2006). Conversely, noise to harmonic ratio (NHR) also features – the inverse of HNR. These measures are carried out on individual vocalisations, and then an average is often taken per session or condition. Another measure of noise is the noise index, as described by Fuamenya et al. (2015). In this technique, the authors used the sum of noise over a total recording session, and divided this by the sum of periodicity of the same session. The noise index therefore calculated as one measurement per session, rather than the average of multiple calculations per session. However as noted in Fuamenya et al. (2015) (and outlined below) the noise index of each session was in fact summed and averaged for each month of recording. Therefore, the noise index could be thought of as essentially analogous to the NHR in previous studies.

Noisiness is most often used in studies to indicate voice disorders such as dysphonia, although this feature is also present in normal infant vocalisations (Fuamenya et al., 2015; Jotz, Cervantes, Abrahão, Settanni, & de Angelis, 2002; Yumoto, Gould, & Baer, 1982). Investigations of the effects of hearing loss (or inversely cochlear implantation) on the voice have also employed noisiness as a suggestion of the degree of laryngeal control.

Noise measurements are able to be taken from a variety of vocal samples; however the most commonly used method in paediatric studies is the production of the sustained vowel /a/. This is often chosen because it is easy for most young children to articulate, regardless of their level of speech development. An example of the way in which children are asked to make this sound was described by Maturo et al. (2012, p. 957); “Subjects were asked to sustain the phrase “ah” at a comfortable pitch and volume using a normal speaking voice for over 4 seconds. After 3 rounds of practice, the fourth production of “ah” was recorded”. Noise studies of early infancy use spontaneous vocalisations such as cries or coos, instead of an intentionally produced sound.

1.9.6 Noise: development in normal hearing infants. Fuamenya et al. (2015) investigated the cries of 20 normal-hearing infants over the first three months of life using the measure of noise index. Over the three months, mean noise index showed a significant decrease from 0.2 in month 1 to 0.08 in month 3. The authors postulate these changes are due to both neural and anatomical changes, demonstrating the ‘fine-tuning’ of phonation development. Maturo et al. (2012) investigated the acoustic features of 335 children between four and 18 years of age in order to establish a normative acoustic database for children. The data for males and females was assessed separately, and the average NHRs of a sustained ‘ah’ vocalisation for the 14 girls and 12 boys who were four years old were both 0.12 (SD = 0.03 and SD = 0.02 respectively). Overall, the average NHR between 4 years and 18 years was 0.11 (SD = 0.02) for girls and 0.12 (SD = 0.03) for boys. The authors note that these values are similar to previous acoustic databases which include the NHR of paediatric voices (Campisi et al., 2005; Tavares, Labio, & Martins, 2010). They also quote the CSL (Computerised Speech Lab software) adult normative value to be 0.19. Tavares et al. (2010) assessed the NHR of 30 males and 30 females between 4 and 5 years old using the sustained vowel /a/, and found NHR averages of 0.132 (SD = 0.03) and 0.135 (SD = 0.022) respectively, whilst Campisi et al. (2005) found the average NHR of /a/ for 50 males and 50 females aged 4-18 years old to be 0.11 (SD = 0.002).

Scheiner et al. (2002) examined preverbal vocalisations of seven normal hearing infants in the first year of life. Although no values were stated, the harmonic to noise (HNR) ratio was said to increase over the period for all types of vocalisations – i.e. the amount of noise in each sample decreased. This was postulated to be due to the strengthening of speech motor control systems. Robb and Saxman (1988) did not measure noisiness directly, but noted that 6% of the noncry samples from 14 NH children aged 11-25 months contained elements perceived to be harsh (such as biphonation, harmonic doubling and f0 shifts).

1.9.7 Noise: development in hearing impaired infants. Dehqan and Scherer (2011) assessed 14 boys with profound hearing losses who wore hearing aids (5-6.75 years old). Measuring /a/, they found a lower HNR (i.e. higher noise ratio) for these boys when compared to their normal hearing peers. This suggests poor laryngeal muscle control, but also that hearing aids may not supply adequate auditory feedback for profound losses.

1.10 Effects of cochlear implantation on acoustic parameters of infant voice.

As expected, many researchers have investigated the effects of CI on vocal parameters of children. These have generally involved cohorts of older infants, such as pre-schoolers (from 3-4 years and older). As the implantation of younger children is a more recent advancement, most studies on young CI recipients have focused on the benefits of early implantation as a broader topic, rather than vocal changes themselves (particularly when these infants are preverbal at implantation). Therefore although this summary has attempted to include the available appropriate evidence of the youngest children possible, many examples have involved children older than 2 years of age. These findings still provide an indication of the effects of cochlear implantation on infant voice, by highlighting the presence and direction of any change seen after implant activation. However the exact parameter values given by these papers are less significant.

Most studies on the effects of CI in children use a non-randomised, pre/post intervention design, taking measures before and after CI activation. Hocevar-Baltezar and colleagues produced two papers in succession of the effects of CI on children's' voices (Hocevar-Boltezar et al., 2006; Hocevar-Boltezar, Vatovec, Gros, & Zargi, 2005). Both studies included CI effects on mean vocal f0 and NHR before and after implant activation, using the sustained vowel /a/. The first involved 31 children (mean age 6.24 years) who were assessed pre-CI and 2, 12, and 24 months post-activation. They found a significant improvement in NHR, and although mean f0 decreased over time, the effect was not significant by the 24 month follow up (Hocevar-Boltezar et al., 2005). Overall, the children implanted before the age of four years showed significant improvements in NHR whereas those implanted after showed significant improvements to f0. The second study compared prelingually deaf children (mean age 5.89 years) to postlingually deaf adults, pre-CI activation and 6 months later. F0 showed no significant improvement in either group, however mean NHR decreased from 0.17 to 0.14 in the children (and showed no change in adults) (Hocevar-Boltezar et al., 2006). The authors theorised that the use of the sustained vowel /a/ instead of standard speech samples may have contributed to the lack of observable change to f0; other authors have also found varying results using /a/.

Monini, Banci, Barbara, Argiro, and Filipo (1997) demonstrated a statistically significant decrease in sustained vowel /a/ f0 for both adults and children immediately after CI switch-on, whilst Campisi et al. (2005) found no significant change to children's /a/ f0 (mean age 10.4 years) up to six months post-activation. More recently, Joy, Deshpande, and Vaid (2017) analysed 30 young children (4.1-6.7 years old) who had been CI users for between 6 months and 2 years. This study analysed the habitual fundamental frequency (HFF) of vowels /a/, /i/ and /u/ and found that the 6 month CI user group fell outside the HFF norms (average HFF of /a/ = 315Hz), whilst the CI users of 2 years approximated norms (average HFF of /a/ = 266Hz). Paediatric norms were stated as 240-280Hz.

Wang et al. (2017) followed 30 children who received cochlear implants between four and six years old for 24 months after implantation. They found that prior to implantation, the f0 of deaf children was significantly higher than that of their normal hearing, age-matched peers. F0 slowly decreased after CI activation and reached levels close to the normal hearing children after 24 months. The normalisation of acoustic parameters after CI use is supported by de Souza, Bevilacqua, Brasolotto, and Coelho (2012), as well as Seifert et al. (2002) who albeit only found a significant deviation from normal f0 values for children implanted after 4 years of age.

Less investigations have been carried out on CI's effect on vocal duration, however an excerpt from a recent presentation found the duration of isolated vowels in two young CI recipients (under 2 years of age) to be longer than that of their normal hearing peers (Binos, 2017, September 21-22). These children were followed for 6 months after CI activation. Shorter vowel durations were associated with greater development of vocal abilities; therefore the findings indicate a weakness for CI's performance. Another study showed that four deaf children of 9-14 years, who had been CI users for 2-4 years, exhibited longer speaking durations (via sentence speech analysis) than sex- and age-matched peers, but their vocal pitch was not significantly different from normal (Perrin, Berger-Vachon, Topouzkhanian, Truy, & Morgon, 1999). Fagan (2014) measured vocal durations of 16 deaf infants and 27 NH infants of the ages 7-11 months (mean age 9.9 months), and then re-measured approximately four months after the deaf infant's CI activation (mean age 17.7

months). Mean vocalisation duration for the deaf infants was 0.633s pre-CI and 0.791s post-CI. In comparison, normal hearing infants vocalised for a mean duration of 0.573s at the first time point, and 0.623s at the second. Although no statistical significance was found, the data does indicate a slight increase in vocal duration for both groups, however CI infants produced longer vocalisations both before and after implantation compared to NH peers. Jafari et al. (2017) compared /a/ f0 and vowel duration between children (mean age 72 months) wearing hearing aids, CIs, and those with normal hearing to find that the f0 of the HA group was significantly higher than NH children. No statistical significance was shown between the f0 of CI and NH children. In contrast, no difference was found in vowel duration between HA and CI, but both groups showed significantly longer vowel durations than their NH peers.

Poissant, Peters, and Robb (2006) employed a different approach to investigating the effects of CI – by measuring the voice of six HI children (average age 7 years, average CI use 2.8 years) with the CI in on/off positions. The f0 of monosyllabic speech words was significantly higher for most children when the CI was turned off, although two children showed the opposite pattern. However this finding shows HI children still somewhat rely on auditory feedback through the CI for pitch control. An earlier, smaller study using older children with CIs (11-14 years old) showed differing results, with the average voice f0 slightly increasing when the implant was switched off (Fourcin, Abberton, Richardson, & Shaw, 2011).

1.11 Review of the Literature

Overall the literature shows that although some classic deviant vocal features can to an extent be expected for infants with hearing loss (i.e. high f0, long vocalisation duration, high proportion of noise), these are far from consistently found when studies are undertaken. Some inherent limitations present themselves both within and between these studies; namely the varying ages of the infants, different treatment of the data (such as inclusion/exclusion criteria), and variations on definitions used for each parameter, as well as the measuring methods undertaken, as Iyer and Oller (2008) addressed. Iyer and Oller approached these limitations from the perspective of noncry f0 studies, but the same critiques can be applied across the field of infant acoustic analysis.

1.11.1 Literature limitations: experimental designs and analyses. The investigations on the voice of NH and HI infants show how age and physiological development affect vocalisations, both with and without the presence of auditory feedback. These confounding factors, such as size and shape of the vocal tract as well as cognitive ability add difficulty to comparing studies of differently aged infants. Investigations such as Hocevar-Boltezar et al. (2005) use a pre- and post-intervention design which reduces the amount of confounding factors, but the paediatric population they assessed was around 6 years old – much older than many children currently undergoing cochlear implantation (James & Papsin, 2004). Therefore, comprehensive evidence of CI vocal effects on young infants is still missing from the literature.

In order to measure an acoustic parameter, each team of researchers must decide upon a definition of their measurement as well as inclusion/exclusion criteria. As Iyer and Oller (2008) describe, for f0 this may include a minimum or maximum f0 value in order to be included in the analysis. For example, those studies which exclude squeals will very likely conclude with lower mean f0 values than studies which do include squeals; likewise the minimum length of vocalisations that were measured may affect the results. The same can be said for noise measurements, when it is up to each researcher to define what counts as ‘noise’ in a sample. These aspects of analysis are often not explained in detail, if at all, in the literature. For example, Maturo et al. (2012) make no clarification on their definition of 'noise' or how this was assessed. The lack of procedural specifications makes it extremely difficult to compare data and give generalised comments on multiple papers.

The procedure of taking measurements and describing these features is particularly important in the analysis of infants and young children, because the amount of possible variation for each definition and method increases as the child ages. Very young infants are generally unable to produce intentional sounds, and so studies focus on spontaneous vocalisations; for example Campisi et al. (2002). As their development increases, many studies opt for the sustained vowel /a/, which has the advantage of being able to be produced by relatively young infants as well as being more dependent on acoustic feedback rather than orosensitive control (Campisi et al., 2005). However, some older studies on school-aged children use speech samples, for example the reading of a text passage or list of words (Poissant et al., 2006), which could give quite different results to a sustained vowel sound.

As previously mentioned, the underlining ethical boundaries of investigating infant development are crucial factors in the variation of results. Research and academic studies are not able to control the age at which children undergo cochlear implantation, and there is no way to feasibly regulate the amount of previous auditory stimulation via hearing aids as well as numerous other factors which may impact their vocal development.

1.11.2 Evidence of auditory feedback within infant voice literature. Literature on auditory feedback effects and the infant voice are still somewhat disconnected. Well established speech models such as DIVA exist, which place great emphasis on auditory feedback in development (Tourville & Guenther, 2011). There are also several studies on the differences between NH and HI vocal development (Maturo et al., 2012; Van Den Dikkenberg-Pot et al., 1998). However few studies are able to directly show the immediate, direct impact of auditory feedback on infant voice, instead taking measurements which are essentially vocal ‘snapshots’ before and after implantation (although there maybe be several snapshots post-CI, e.g. Hocevar-Boltezar et al. (2005). It is likely that some acoustic changes can occur in a much shorter time frame than these studies represent. This may be partly due to the relatively recent introduction of implantations for infants under one year of age, but also a lack of appropriate data in order to facilitate valid analyses. To ideally study the impact of auditory feedback on voice, the infants need to be old enough to produce well developed vocalisations (albeit with deviations from the norm), have had extremely limited past access to auditory feedback, be chronologically within the sensitive period of audiological development as well as be independently undergoing cochlear implantation that can be closely followed.

1.12 Statement of the Problem

Many of the aforementioned studies provide useful information on the acoustic features of children’s speech following CI activation and provide some evidence of the effect of auditory feedback on infant vocal development. Nevertheless there remain few reports which investigate young infant vocal changes before, during, and after speech on a longitudinal frame. This would add to the current literature base by providing information on short-term effects of auditory feedback restoration, rather than snapshots of infant voice after weeks or months have passed. The data accessed for this thesis are unique in the sense that it allows for week-by-week analysis of changes to the two toddler’s vocal features as their auditory environment changes by way of the type of auditory prosthesis worn. It is also unique because neither child had extensive experience of hearing aid wear before the recordings began (they had only worn the aids for a short time before CI activation was carried out), and they both received CIs at an older age than most congenitally deaf infants currently do. This means that the children will be essentially moving from a state of prolonged near-full auditory deprivation to auditory stimulation (as complete as is currently possible) with the activation of the CIs.

The research question posed for this study is: how do the acoustic features of the vocalisations of two congenitally deaf toddlers change longitudinally pre- and post-cochlear implantation, in response to restored auditory feedback?

1.13 Study Hypotheses

1.

H_1: Duration of vocalisations decreases upon CI activation

H_0: Duration of vocalisations do not decrease upon CI activation

2.

H_1: Vocalisation f0 decreases upon CI activation

H_0: Vocalisation f0 does not decrease upon CI activation

3.

H_1:Noise Index decreases upon CI activation

H_0:Noise Index does not decrease upon CI activation

4.

H_1: The pattern of variation of these acoustic parameters will be at a stable baseline prior to CI, and increase post-switch on.

H_0: The patterns of variation do not change upon CI activation

2 Methodology

The data for this study consisted of vocal recordings from two toddlers, which had been previously gathered by the Centre for Pre-Speech Development & Developmental Disorders at the University of Würzburg (Germany), under the direction of Prof. Kathleen Wermke. The speech recordings and corresponding spectrographic images were a part of the Centre's acoustic database of pre-linguistic and early linguistic development in children. Prof. Wermke provided the processed speech recordings and spectrographic images, as well as the methodological information on data collection detailed below. At the time of data collection, approval was given from the Ethics Committee of the University of Würzburg (Approval number 143/04).

2.1 Participants

Vocal recordings from four toddlers were provided by Prof. Wermke. The data of two toddlers were discounted from this analysis as there was deemed to be an insufficient amount of vocalisations recorded either pre- or post-cochlear implantation. The recordings for the remaining two toddlers covered at least 3 weeks of the pre-implantation and post-switch on stages, as well as the interim period between implantation surgery and CI switch-on. Both toddlers were admitted to the otolaryngology clinic at the University of Würzburg (Klinik und Poliklinik für Hals-, Nasen-, und Ohrenkrankheiten, plastische und ästhetische Operationen, Universitätsklinikum Würzburg) and underwent cochlear implantation between February 2004 and September 2005. They both presented with congenital, bilateral profound sensorineural hearing losses with negative histories of metabolic disease, cognitive impairment or multiple disabilities.

2.1.1 Participant 1: AD. This child was diagnosed with a hearing loss at the age of 2 days old following otoacoustic emission (OAE) and auditory brainstem response (ABR) testing.

The results of the ABR showed no response to sounds up to 90dB HL in the right ear and no response to sounds up to 100dB HL in the left ear. This indicates AD was born with a profound bilateral sensorineural hearing loss, with the cause attributed to hereditary disease. He was provided with bilateral hearing aids at 80 days (2.5 months) old, however his mother reported that he did not readily accept these and she did not notice any behavioural changes when he wore them. For these reasons, his mother did not believe the hearing aids were providing benefit to her son, and AD wore the aids infrequently until after CI surgery. AD underwent cochlear implantation surgery on the right side at 359 days (approximately 12 months) old, with the initial switch-on of the device occurring 44 days later when he was 403 days (13 months) old. He was fitted with a Pulsar 100 CI by MED-EL. In the period between the surgery and CI switch-on, AD wore a hearing aid on the left side. He also continued to wear the left hearing aid after CI switch-on. A total of 21 occasions of vocal recordings were analysed, between the ages of 332 days old and 423 days old, with a sum of 1050 vocal sounds examined.

2.1.2 Participant 2: AE. AE was referred for audiologic assessment at 407 days (15 months) old, when her parents became concerned of her lack of language development. Prior to this, her mother had approached the paediatrician several times with concerns over AE's lack of babbling compared to her peers, which the doctor had attributed to a slight developmental delay. AE's mother maintained concerns regarding her daughter's hearing, and so self-referred AE to the ENT clinic at the University of Würzburg. Her subsequent ABR testing at 464 days (15.5 months) old showed a bilateral profound sensorineural loss, with no response up to 100dB HL in the left ear and no response up to 90dB HL in the right ear. The cause of this hearing loss was described as idiopathic. Because of the late diagnosis, AE wore bilateral hearing aids for a short period (four weeks total, from 475 days old) before she underwent CI surgery at 506 days (16.9 months) old. Her initial CI switch-on occurred 46 days later at 552 days (18.4 months) old. AE did not continue to regularly wear a hearing aid on the left side during the time between surgery and switch-on (except for day 550), nor did she resume wearing it after CI switch-on. A total of 13 occasions of vocal recordings were analysed, between the ages of 477 days old and 575 days old, with a sum of 629 vocal sounds examined.

2.2 Data Collection

The total recordings provided for child AD were made between 09/12/04 and 22/06/05, from 300 days old until 495 days old. Recordings provided for child AE were made between 21/01/05 and 18/07/05, from 465 days old until 643 days old. The recording sessions were organised to be approximately weekly (± 4 days), and were carried out during appointments in the ENT clinic at the University of Würzburg and at the children's homes. The aim was to record spontaneous vocal utterances of the children. Each child's parents were provided with training and instructions on carrying out the recordings to ensure they were as consistent as possible. As recordings in the home environment brought more drawbacks such as environmental and speech background noises, the frequency and length of these recordings was increased at times. Child AD's spontaneous vocal utterances were recorded with a Sony TCD-D3 recorder before the 23/03/05 and a Tascam –DA-P1 thereafter, whilst child AE's utterances were recorded with a Tascam DA-P1 recorder.

2.3 Data Processing

The recordings provided for this thesis had already been processed at the Centre for Pre-Speech Development & Disorders at the University of Würzburg. CSL 4400, software by KAY Elemetrics was used in conjunction with a cry data analysis programme (CDAP by pwproject) in order to analyse the data and process it into computable sound files. Signals of interest (all those including vocal utterances) were identified using auditory vocal analysis and segmented by separating them at the end of each expiration by the child. The files were then processed into WAV format, and organised according to recording day. Overly noisy or otherwise poor recordings were omitted. Spectral analysis was carried out using an additional MDVP module, and screenshots of these spectrograms were provided with the processed sound files.

2.4 Data Analysis

The sound files collected for AD and AE were further analysed in the present study. Auditory and spectral analyses were carried out in order to assess the type of vocalisation and introduce further inclusion/exclusion criteria. All spontaneous vocal utterances that were not jointly judged by the researcher and Prof Wermke to be comfort sounds were excluded. This included cries, laughs, gurgles and raspberries; however non-distress squeals were retained. Several sound files contained too much background noise to be assessed accurately, and so were also discounted. Any vocalisations that were measured to have duration of less than 300ms were rejected, as this is commonly used as a minimum comfort sound length in speech and language analyses (Gregory, Tabain, & Morgan, 2010). The data also included longer files of multiple vocalisations, called series recordings. These were included to show how some of the sounds fit together in time, but were not necessary for this analysis.

Data analysis was carried out using version 6.0.28 of Praat speech analysis software (Boersma, 2017). The data were imported into Praat and visualised as a narrowband spectrograms (view range: 0-5kHz, window length: 0.3s, dynamic range: 70dB) and a raw waveform. These two visual representations of the data were used in conjunction with auditory/perceptual assessment to evaluate the duration, f0 and noise index of each sample. The definitions and measurement processes of these acoustic features were based on a previous f0 and noise analysis by Fuamenya et al. (2015).

2.4.1 Duration. Duration was defined as the time between the onset and offset of visible acoustic energy “in the expiratory phase of a single respiratory cycle”. To measure vocal segment duration, vertical cursors were placed at the point of onset and offset of the spectrogram and the duration noted. An example of measuring duration is included (Figure 2.1).

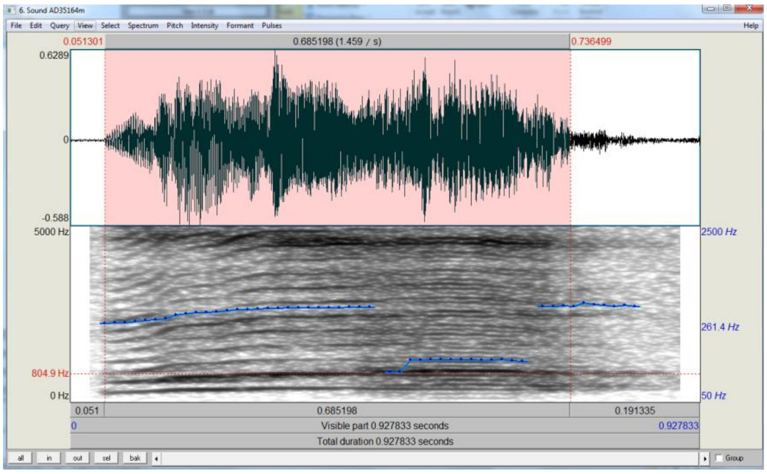

Figure 2.1. Visualisation of the measurement of vocal segment duration . The cursors were placed around the vocal segment (highlighted in red). The selected duration is depicted in seconds at the top of the Praat spectral analysis view.

2.4.2 Fundamental Frequency. F0 was defined as the lowest visible frequency band in the periodic segments of the sample. In order to be defined as a periodic segment, at least two bands of harmonics were required to be visible (f0 and f1) on the spectrogram. In addition, these segments needed to have the sound qualities typical of a periodic signal (e.g. ‘clean’, tone-like) by auditory assessment. The dynamic range of the spectrograms was decreased to 30-40dB on occasion in order to confirm the presence or absence of periodicity by way of the f0 and first harmonic. Periodic portions of the vocalisation segment that were analysed for f0 were at least 50ms in length. The f0 was quantified by using the ‘Get Pitch’ function in Praat which superimposes a quantifiable pitch curve onto the spectrogram, as displayed in Figure 2.2. The unit of the pitch curve was set to Hz (logarithmic), which measures the average of the logarithms of the pitch values in a given selection of the sample, and then transforms the result back to Hz. This gives a result which is equivalent to the geometric mean pitch of the selected sample, allowing for a better representation of the overall f0 and giving less emphasis to any extreme values.

For each sample, the pitch line was examined to ensure it correctly fit the f0 band. In cases where the software had inaccurately measured another harmonic other than f0, the pitch range was adjusted to rectify the error. Sometimes this had to be adjusted several times for one sample in order to find an appropriate mean f0 (see Figure 2.3). For samples which contained noise segments in the middle of periodic parts of the vocalisation, several different methods of analysis were carried out. When the average pitch segments were of a similar f0, the segment with the longest duration (which was also acoustically and visually judged to be a good representation of the sample) was used to calculate f0 by placing cursors around this area of the spectrogram and using the ‘get pitch’ function of Praat.

On occasions where the initial onset of vocalisation was the longest duration of periodicity but did not accurately represent the f0 of the rest of the sample, the next longest periodic segment was used (as long as this still met the >50ms criteria). On others, short bursts of noise (<100ms) interrupted the periodic parts of the vocalisation. By adjusting the pitch range, it was possible to either avoid the pitch line measuring the noise at all, or ensure that the pitch line stayed consistent to the f0 band through the noise. In order to gain as good a representation of the entire sample as possible, mean f0 was taken through these noise points. When it was not possible to accurately measure through the noise portions, and the f0 showed observable variability (e.g. pitch shifts or large fluctuations in f0), several mean f0 were taken for the sample and the average of these numbers was used. To increase accuracy when multiple f0 were taken and averaged, the duration of each measured f0 portion was kept consistent for the sample. For several of the vocalisations, an echo of the former f0 after a pitch shift was detected by the Praat pitch function, and not able to be adjusted. In these few cases, the pitch curve did not entirely represent the f0 of the sample but was still judged to be a fair representation.

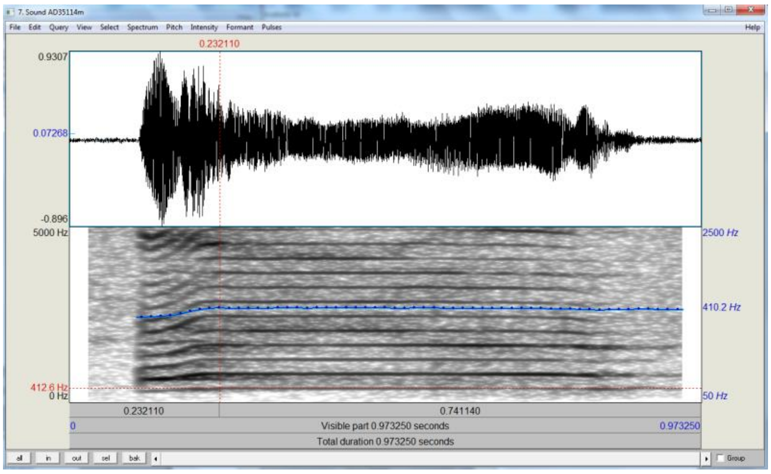

Figure 2.2. Example of pitch measurement in Praat . The pitch contour is shown as a blue line. This was confirmed to be accurate by using the cursor to find the frequency of the lowest visible spectrogram band, depicted by the horizontal red line.

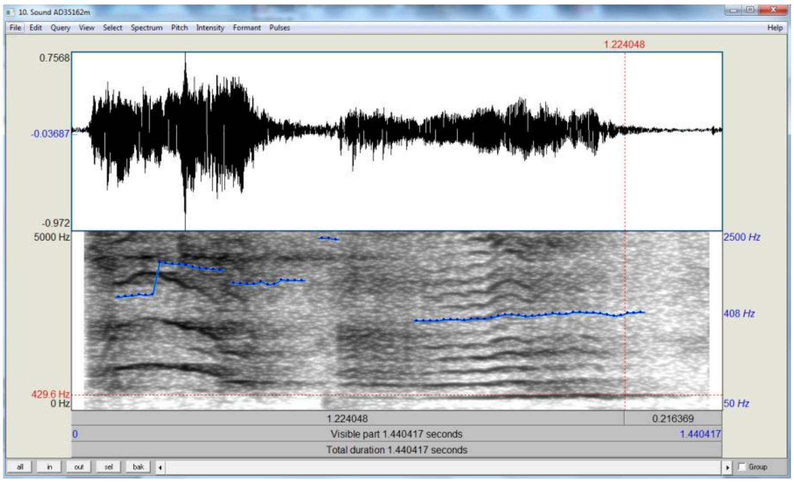

Figure 2.3: Spectrographic example of pitch shifts within a single vocal segment , separated by a period of noise. The blue pitch contour is seen to accurately measure the pitch of the second periodic segment, but not the first.

2.4.3 Noise. The definition of noise was adapted from Fuamenya et al. (2015) and Robb (2003): any part of the signal where there was either the absence of a clearly visible f0 and harmonics, the presence of subharmonics, and/or the acoustic features of noise (a 'roughness' quality to the sound) for a length of at least 50ms. This was measured by placing vertical cursors around each noise band in a recording and summing the noise duration.

The two predominant types of noise identified in the recordings were subharmonics (see Figure 2.4) and pulse register phonation ('vocal fry'; see Figure 2.5). Vocal fry was defined as "the appearance of very closely spaced harmonics often resulting in temporal resolution of individual glottal pulses in the waveform and sometimes also the spectrogram, and a clear perception of a low "zipper-like" quality" (Buder et al., 2008, p. 6). In some recordings, the quality of the recording was too low to show the glottal pulses in the spectrogram, in which case acoustic analysis was predominantly used to identify the creaky, rough sound characteristics of vocal fry. Upon evaluation of the data, it was found that vocal fry could be identified more readily and accurately by using a combination of auditory and spectral analysis rather than spectral analysis alone. This was supported by the identification of vocal fry by Prof. Wermke. Subharmonics were defined as “the abrupt appearance in the narrowband spectrogram of intervening harmonics, doubling, tripling, or even higher integer multiples in relation to the surrounding set” (Buder et al., 2008, p. 6). These were more easily identifiable by spectrogram visualisation, but sometimes required changing the dynamic range for confirmation. Some frequency shifts contained reverberations that appeared on the spectrogram in a similar manner to subharmonics, but these were not included as noise – often measuring less than 50ms or missing the acoustic characteristics of subharmonics.

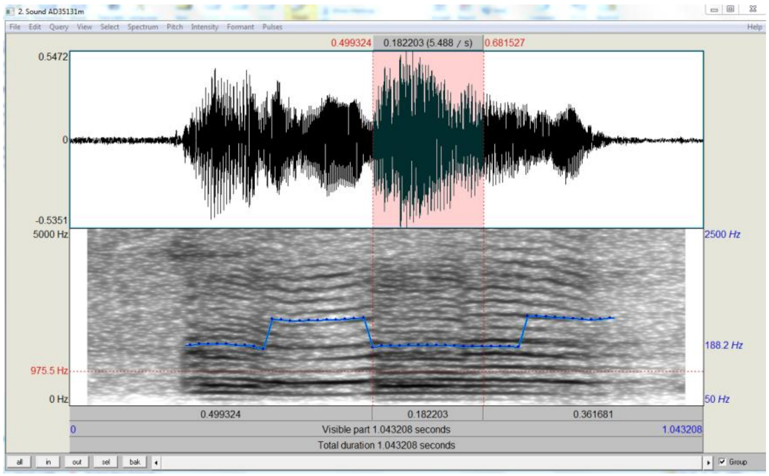

Figure 2.4. Spectrographic example of subharmonics within a vocal segment. Cursors have been placed around one of the subharmonic sections and the duration of this noise is displayed at the top of the software.

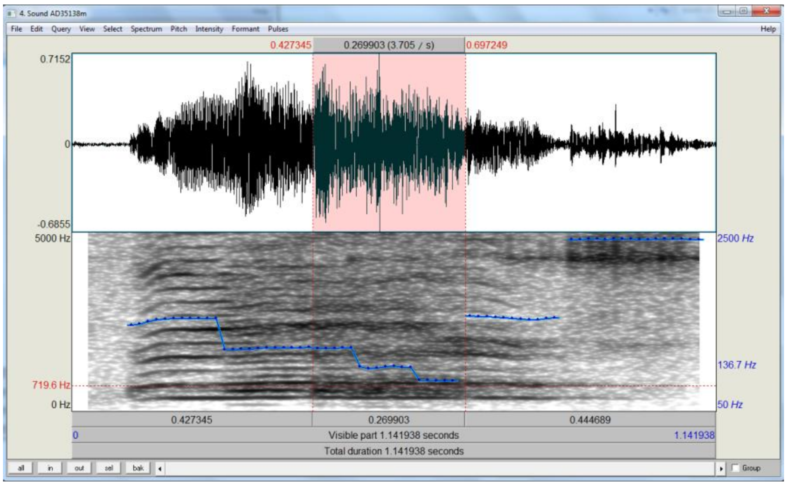

Figure 2.5. Spectrographic example of pulse register phonation (vocal fry) within a vocal segment. Cursors have been placed around the section of vocal fry, and the duration of this segment is displayed at the top of the software

2.4.4 Calculation of Noise Index. The calculation of a Noise Index (NI) was based on the previous paper by Fuamenya et al. (2015). This was defined as the proportion of the total recording which consisted of noise, and was calculated by dividing the amount of noise by the total duration for each sample. In Fuamenya et al. (2015), an NI was calculated per recording session (summing the individual noise segments as well as the total duration of each segment, and then dividing these), however for this study an NI was calculated for each cry, which were then summed and averaged for each recording session.

The features above were measured for each cry sample that met the inclusion criteria and contained at least 50ms of periodicity. For recordings that were deemed 100% noise, no f0 was recorded and NI was measured as 1. If no noise of >50ms was present in the sample, NI was recorded as 0.

3 Results

The results are presented in two sections. The first section comprises the acoustic analysis of child AD and the second covers the analysis for child AE. The analyses include data for f0, duration, and noise index (NI) for each vocal segment. The participants' data analyses are divided into three phases: before CI surgery (Phase 1), after CI surgery and before CI switch-on (Phase 2), and after CI switch-on (Phase 3).

For child AD, Phase 1 includes recordings measured over the three weeks immediately pre-surgery (six separate recording sessions). He typically did not wear hearing aids during these sessions. Phase 2 covers a period of four weeks post-surgery and pre-switch on, starting two weeks after surgery (seven sessions total), when he generally wore a hearing aid on his left side. Phase 3 includes three weeks post-switch on (eight sessions), predominantly conducted with the CI on and no hearing aid worn on the left side.

Child AE's first Phase comprises the three weeks prior to surgery, when she typically wore hearing aids bilaterally (three sessions total). Phase 2 began one week after surgery, and included six sessions over the subsequent five weeks when she did not use amplification. Phase 3 includes three sessions over the three weeks after CI switch-on, when the CI was activated on the right and no hearing aid was worn on the left.

Each dependent variable (f0, duration, NI) is represented by way of phase-specific histograms and a box and whisker plot. In order to facilitate visualisation and comparison between the two participants, the histogram bins and x-axis maximums for each corresponding measure were equalised. Due to the wide range in acoustic values, the f0 data were plotted using a logarithmic scale. No such transformation was performed for duration and NI. The log10-f0 histograms are displayed according to frequency bins of 25Hz. The duration results are presented in histograms according to bin lengths of 250ms. The NI results are displayed in histograms according to a bin length of 0.1.

3.1 Child AD

The weekly results across the three phases for each acoustic measure are displayed in Table 1. These same results are displayed as Figures in Appendix A. A summary of the results as described per Phase is given in Table 3. Collectively, Phase 1 included a total of 283 vocal segments. Phase 2 contained 236 vocal segments and Phase 3 contained 289 vocal segments.

3.1.1 Duration. The durations of child AD's vocalisations across the three phases are shown in histogram form in Figure 3.1 and box and whisker form in Figure 3.2. During Phase 1, the mean duration was 1.09s (SD = 0.65; Md = 0.91). This increased to 1.29s (SD = 0.75; Md = 1.29) during Phase 2, and further to 1.71s (SD = 0.91; Md = 1.59) in Phase 3.

Examination of the histograms shows that durations are initially skewed to the left in Phase 1, but the central spread of values moves to the right over the three phases. This indicates a general increase in the duration of vocal segments and the data displays a more normal distribution by Phase 3. A prominent modal peak is seen at 0.5-0.75s in Phase 1, whereas Phase 2 shows the modal peak at 0.75-1s. By Phase 3, the histogram takes on a bimodal shape, with the most prominent peak at 1.75-2s. After each modal peak the distribution of data steeply declines; indicating that the phase distributions are still somewhat skewed to the left over each phase.

The medians values and spread of durations for each phase are illustrated in Figure 3.2 in the form of box plots. An overall increase in range is apparent over the three phases; particularly in the lower 50% of values (the lower quartile and whisker). The increase in the lower quarter leads to an increase in the overall interquartile range. The median duration also visibly increased from Phase 1 to Phase 3, and more outliers of longer durations were seen once the CI was switched on. Therefore across the three phases, there was both an increase in the range of vocal durations (also indicated by the standard deviation values), as well as an increase in the mean and median durations. It must be noted vocal segments of less than 300ms were not analysed, and so this was consistently the minimum duration measured across the phases.

The variation of mean duration decreases after CI switch-on. The CV of mean duration is 60% for Phase 1, which decreases to 58% for Phase 2 and further to 53% for Phase 3.

3.1.2 Fundamental Frequency. Figure 3.3 displays the results for f0 plotted in a logarithmic scale over the three phases. Mean f0 increased between Phase 1 and Phase 2, from 471Hz (SD = 309; MD = 360Hz) to 698Hz (SD = 531; Md = 422.82). During Phase 3, mean f0 decreased to 619Hz (SD = 455.38; Md 432.74).

The histograms of Figure 3.3 show the f0 data consistently skewed to the left, towards lower f0 values. The modal peak of Phase 1 is seen at 250-375Hz; whereas in Phases 2 and 3 it is apparent at 375-500Hz. Phases 2 and 3 also indicate the presence of a greater number of higher f0 vocalisations, particularly above 1500Hz.

Although the mean values show this increase and then subsequent decrease, median f0 did not follow a similar pattern. As evidenced in Figure 3.4, the median value showed a consistent rise over the three phases of data collection. The interquartile range was smallest for Phase 1 and largest for Phase 2. Figure 3.4 also indicates the change in the spread of f0 data; the upper quartile and upper whisker are noticeably longer in Phase 2 than Phases 1 and 3, indicating a larger increase in the ranges of the upper 50% of values. This again illustrates the increase in vocalisations with a high f0.

The variation of mean f0 increases after CI switch-on when compared to Phase 1 (no amplification), however the highest amount of variation is noted in Phase 2, when hearing aids are worn consistently for the first time. The CV of Phase 1 is given as 66%, Phase 2 as 76% and Phase 3 as 74%.

3.1.3 Noise Index. Figure 3.5 displays the change in child AD's NI values across the three phases. Mean NI increases over time, from 0.25 (SD = 0.29; Md = 0.17) in Phase 1 to 0.31(SD = 0.30; Md = 0.24) in Phase 2 and 0.36 (SD = 0.31; Md = 0.30) in Phase 3.

Over the three phases, the spread of data does not change greatly, except for a reduction in the size of the large modal peak at 0-0.1. In general, the histograms illustrate an increase in uniformity of NI values by Phase 3.

The box and whisker plots of figure 3.6 also indicate this uniformity by Phase 3, with median NI values rising across the time periods. Calculated NI values are between 0 and 1, and so although the range of values doesn't change there is a general smoothing of distributions around the median, and the interquartile range increases. For example, in phases 1 and 2 the lower 50% of values are so concentrated that there is no observable lower whisker. This emerges in the Phase 3 boxplot.

Out of the 283 vocalisations analysed in Phase 1, 176 contained at least some noise and so were calculated to have a NI above 0. This equates to approximately 62% of the vocal segments containing noise. In Phase 2, 169 samples out of 236 were found to have a noise index of more than 0 (71% of the segments), and in Phase 3 this figure increased to 227 out of 289 segments (78%). Therefore the amount of vocal segments containing noise consistently increased across the three data collection periods, just as Figures 3.5 and 3.6 indicate amount of noise within each sample also increased.

The variation of mean NI decreases with the activation of CI. The CV of Phase 1 is given as 116% which decreases to 97% in Phase 2 and further to 86% in Phase 3.

Table 1. *Average vocal parameters per session for Child AD*

	Age (days)	n	Duration (s)		Fundamental Frequency (Hz)		Noise Index	
			Mean	SD	Mean	SD	Mean	SD
Phase 1	332	59	1.37	0.95	349.86	128.68	0.17	0.17
	334	11	1.09	0.41	389.51	193.16	0.11	0.11
	335	73	1.15	0.62	423.48	194.00	0.21	0.26
	351	73	0.89	0.38	603.40	425.04	0.41	0.33
	354	9	0.54	0.15	743.66	520.28	0.28	0.32
	355	58	1.07	0.56	477.47	283.81	0.22	0.29
Phase 2	373	45	1.16	0.82	871.12	549.60	0.21	0.24
	381	50	1.22	0.63	630.46	456.18	0.34	0.30
	388	11	1.17	0.61	459.27	109.06	0.24	0.29
	390	9	1.53	0.60	656.22	452.99	0.19	0.18
	391	55	1.11	0.59	938.1	669.90	0.42	0.32
	392	35	1.06	0.73	548.24	514.91	0.12	0.19
	402	31	2.14	0.66	423.97	101.54	0.50	0.30
Phase 3	403	51	1.95	1.09	638.28	422.06	0.46	0.34
	404	13	1.71	0.82	918.08	685.94	0.40	0.31
	405	14	0.88	0.35	722.58	660.22	0.55	0.39
	406	6	1.40	0.62	559.47	511.27	0.42	0.41
	409	16	0.92	0.44	1636.0	850.62	0.12	0.21
	410	85	1.72	0.55	539.87	228.82	0.41	0.30
	417	51	1.71	0.80	451.48	96.28	0.29	0.22
	422	21	1.26	0.63	577.87	211.42	0.19	0.28
	423	32	2.33	1.37	450.30	228.26	0.28	0.28

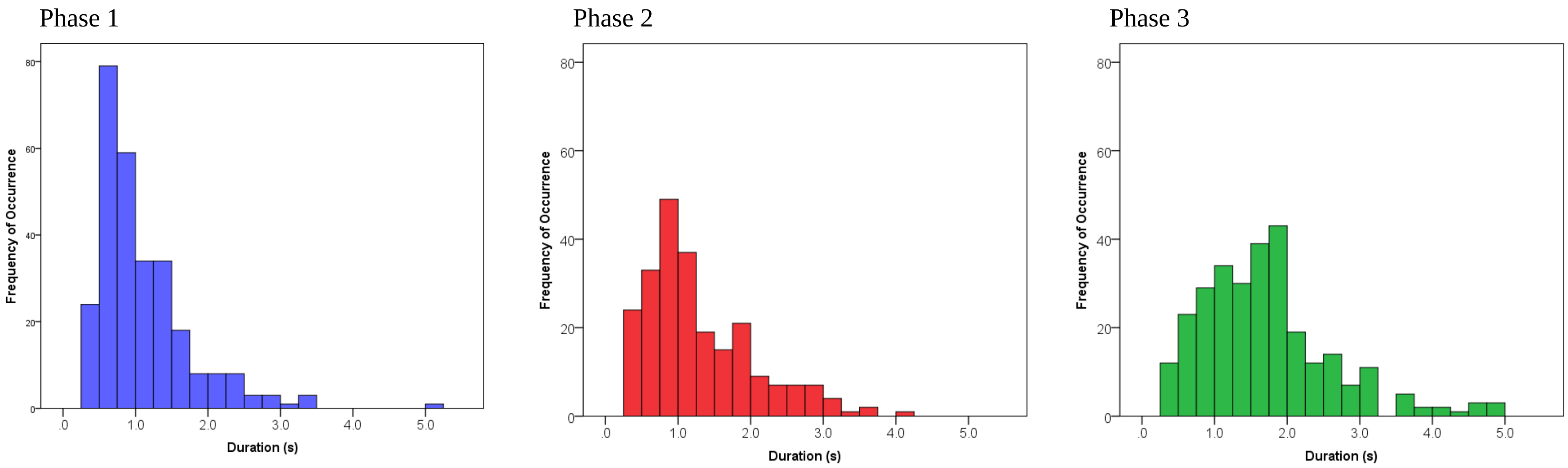

Figure 3.1. Distribution of vocalisation durations for child AD during Phases 1-3. Each histogram represents a bin length of 250 msec.

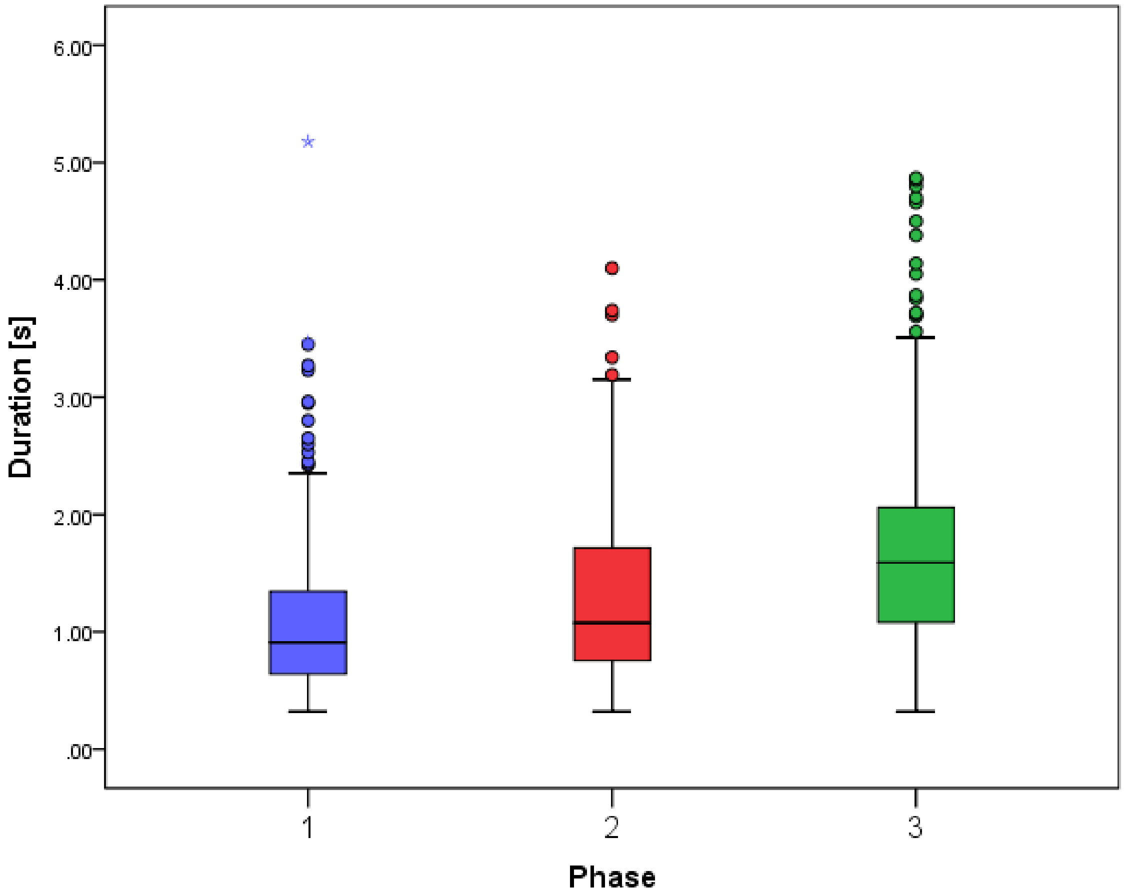

Figure 3.2. Median duration of vocalisations produced by AD across the three phases of data collection.

Phase 1 Phase 2 Phase 3

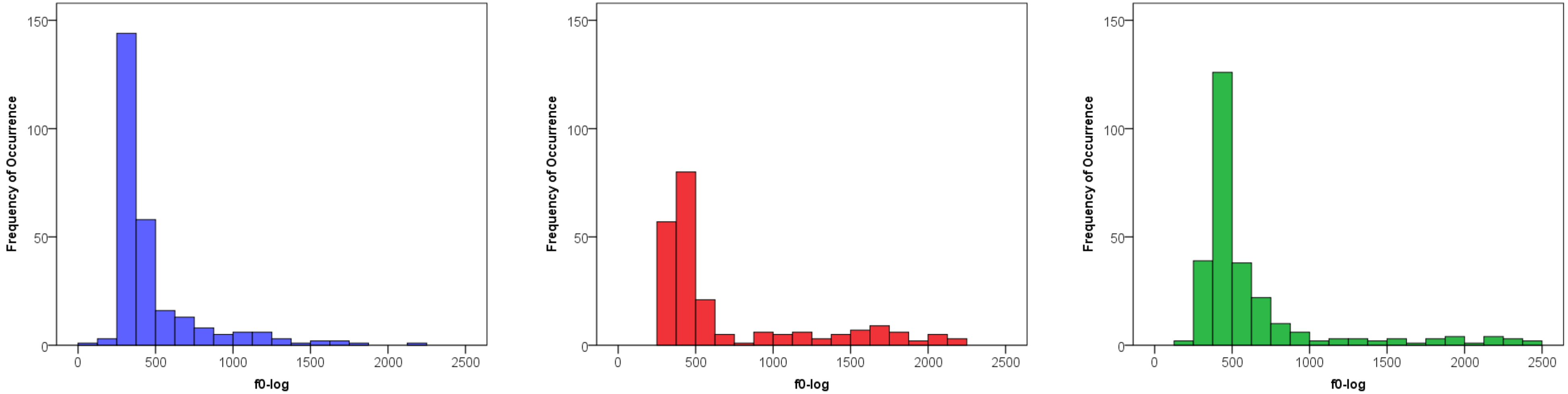

Figure 3.3. Distribution of vocal segment f0 for child AD during Phases 1-3 plotted according to a logarithmic scale. Each histogram represents a bin length of 125 Hz.

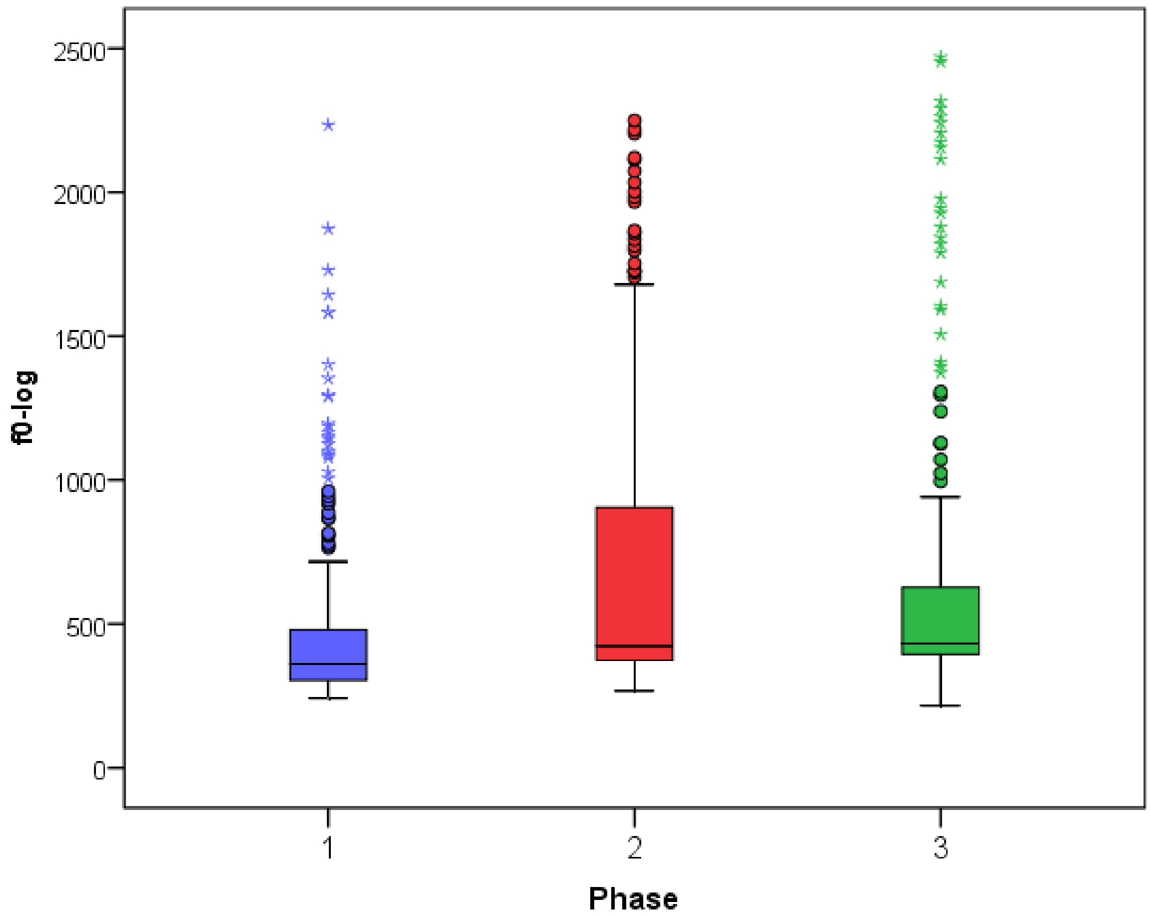

Figure 3.4. Median f0 of vocalisations produced by AD across the three phases of data collection.

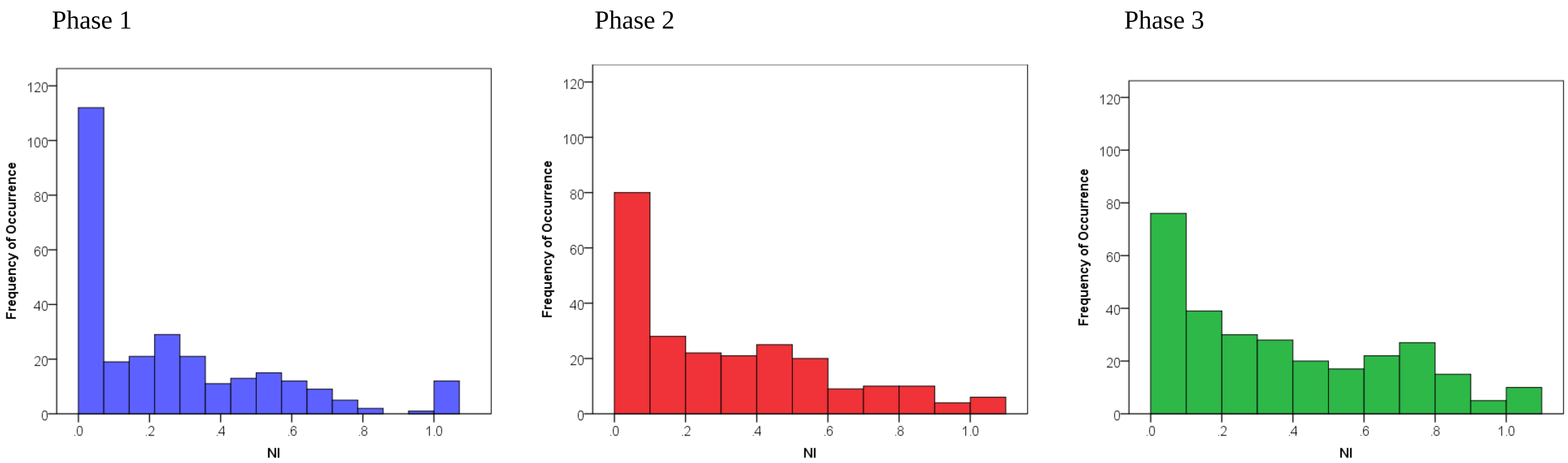

Figure 3.5. Distribution of vocalisation noise index (NI) for child ADduring Phases 1-3. Each histogram represents a bin length of 0.1.

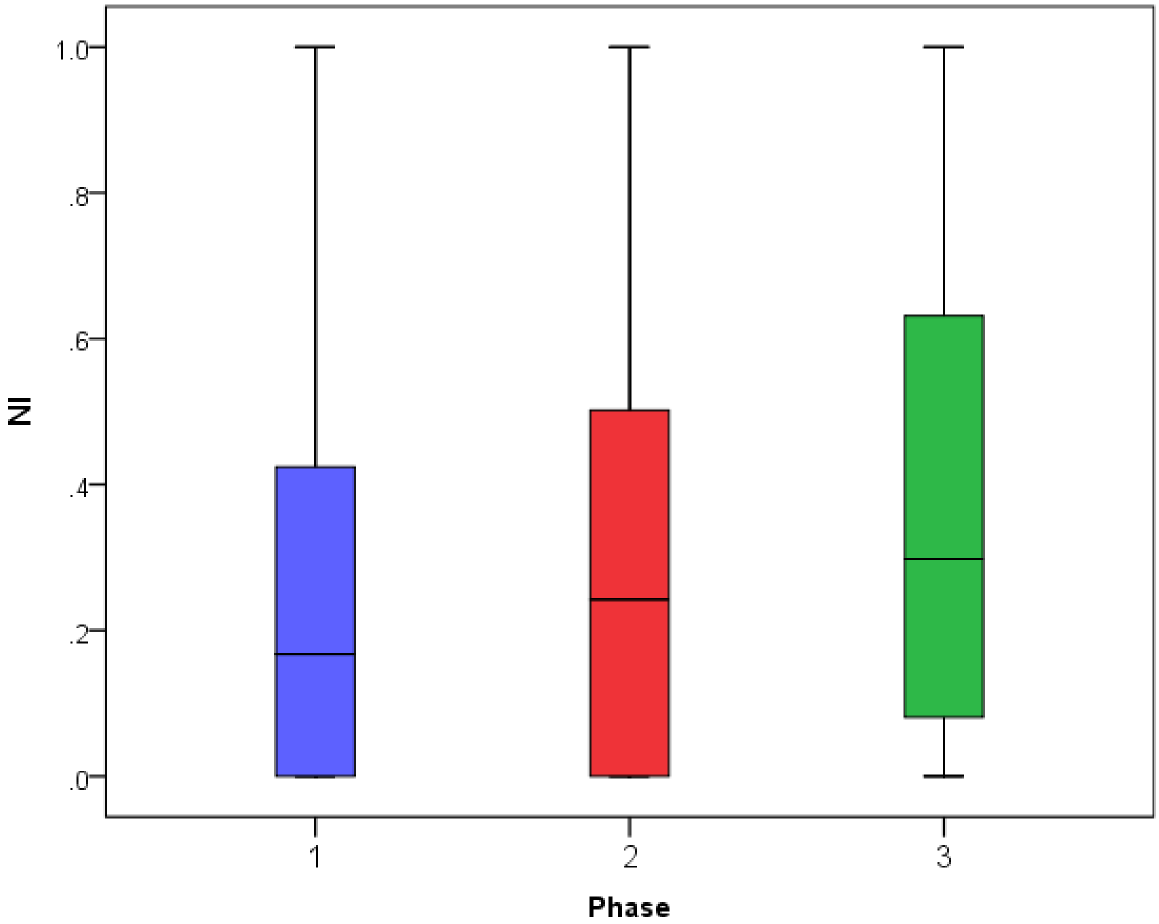

Figure 3.6. Median noise index (NI) of vocalisations produced by AD across the three phases of data collection.

3.2 Child AE

The weekly results for each acoustic measure are displayed across the three phases in Table 2. These same results are displayed as figures in Appendix B. The per-phase results are described below, as well as summarised in Table 3. Collectively, Phase 1 included a total of 131 vocal segments, Phase 2 contained 212 vocal segments and Phase 3 contained 130 vocal segments.

3.2.1 Duration. The duration of vocalisations for child AE are shown in Figures 3.7 and 3.8. Mean duration increases over the three phases, from 0.95s (SD = 0.64; Md = 0.75s) in Phase 1, to 1.25s (SD = 0.76; Md = 1.04s) in Phase 2, and 1.32s (SD = 0.70; Md = 1.20s) in Phase 3.

The histograms in Figure 3.7 show a prominent modal peak emerging between Phase 1 and Phase 2 at 0.5-0.75s, which is then absent in Phase 3. By Phase 3, the spread of data has become more uniform, with a reduction in the observable left-skewness distributions of Phases 1 and 2. Overall, the range of the data does not appear to change.

The median duration also increases throughout the phases, as illustrated in Figure 3.8. A larger spread of the upper 50% of values is seen between Phase 1 and 2, which then decreases in Phase 3. However, the spread of the lower 50% of values increase continuously from Phase 1-3. The lower quartile (and therefore interquartile range) increases, and data appears more evenly spread around the median.

The variation in vocal segment duration is lower in Phase 3 than Phases 1 and 2. In Phases 1, CV = 67%, which decreases to 61% in Phase 2 and further to 52% in Phase 3.

3.2.2 Fundamental Frequency. Figures 3.9 and 3.10 show the f0 values over the three phases for child AE. Mean log10-f0 increased from 504 Hz (SD = 226; Md = 431 Hz) in

Phase 1 to 512 Hz (SD = 265; Md = 429 Hz) in Phase 2, and further to 537 Hz (SD = 316; Md = 413 Hz) in Phase 3.

The histograms of Figure 3.9 illustrate a slight increase in the amount of vocal segments with a higher f0 in phases 2 and 3 compared to Phase 1. They also show a more prominent modal peak at 375-500Hz in Phase 2 than phases 1 and 3, although a similar peak is apparent in Phase 1.

Similarly, the median values across the three recording phases only slightly increased, as evidenced in Figure 3.10. The spread of vocal segment f0 is also very consistent. A slightly greater spread of values can be seen in phases 1 and 3 than in Phase 2. Phases 2 and 3 display more outlying vocal segments with a high f0 than Phase 1.

The variation in vocal segment mean f0 increases after CI switch-on in Phase 3 when compared to the previous two stages. The CV of f0 is measured as 45% in Phase 1 which increases to 52% in Phase 2, and further increases 59% in Phase 3.

3.2.3 Noise Index. Figures 3.11 and 3.12 display the NI data for child AE's vocal segments over the three collection periods. Over this time, the mean NI increases from 0.23 (SD = 0.31; Md = 0.10) in Phase 1 to 0.30 (SD = 0.33; Md = 0.21) in Phase 2, and then decreases to 0.16 (SD = 0.27; Md = 0.00) in Phase 3.

Figure 3.11 illustrates that the proportion of data with an NI of 0-0.1 increases in Phase 3 compared to Phases 1 and 2, while the proportion of data with an NI higher than 0.1 decreases.

Figure 3.12 shows comparable changes to the median values; which increases between Phase 1 and 2, and then decreases in Phase 3 to 0 – the lowest possible value. The variation in each quartile is greater in Phase 2 than Phases 1 and 3; particularly when examining the range of the lower 50% of values. As evidenced by no observable lower quartile or whisker, over 50% of vocal segments in Phase 3 have an NI of 0 (i.e. no noise present in the sample). Only a small number of vocal segments were measured to have an NI of over 0.7 in phases 1 and 3, with few outliers noted for these plots.

The variation in mean NI increases after CI switch-on when compared to the previous two Phases. The CVs of each Phase are as follows: Phase 1 = 135%, Phase 2 = 110% and Phase 3 = 169%.

The proportion of total vocal segments containing noise increases from 60% in Phase 1 (78 out of 131 segments) to 66% in Phase 2 (140 out of 212 segments), and then decreases to 42% in Phase 3 (55 out of 130 segments)

Table 2

Average vocal parameters per session for Child AE

	Age (days)	n	Duration (s)		Fundamental Frequency (Hz)		Noise Index	
			Mean	SD	Mean	SD	Mean	SD
Phase 1	477	33	0.59	0.29	433	140	0.22	0.33
	485	41	0.83	0.55	506	323	0.32	0.38
	502	57	1.23	0.72	540	186	0.16	0.21
Phase 2	521	43	1.04	0.54	429	159	0.20	0.26
	531	37	1.05	0.73	443	95	0.18	0.20
	537	36	1.05	0.60	480	314	0.24	0.33
	541	64	1.46	0.78	667	337	0.39	0.34
	550	32	1.52	0.95	448	160	0.46	0.37
Phase 3	554	45	1.27	0.68	783	390	0.16	0.21
	565	50	1.32	0.69	385	66	0.20	0.30
	572	13	1.04	0.86	417	82	0.11	0.28
	575	22	1.58	0.60	420	234	0.13	0.27

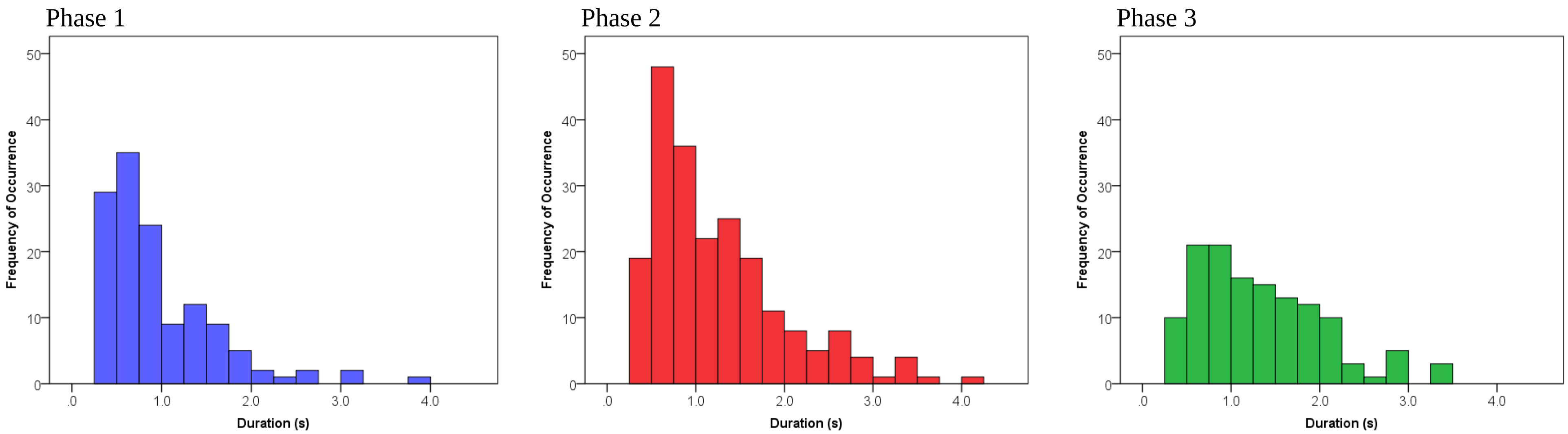

Figure 3.7. Distribution of vocalisation duration for child AE during Phases 1-3 . Each histogram represents a bin length of 250ms.

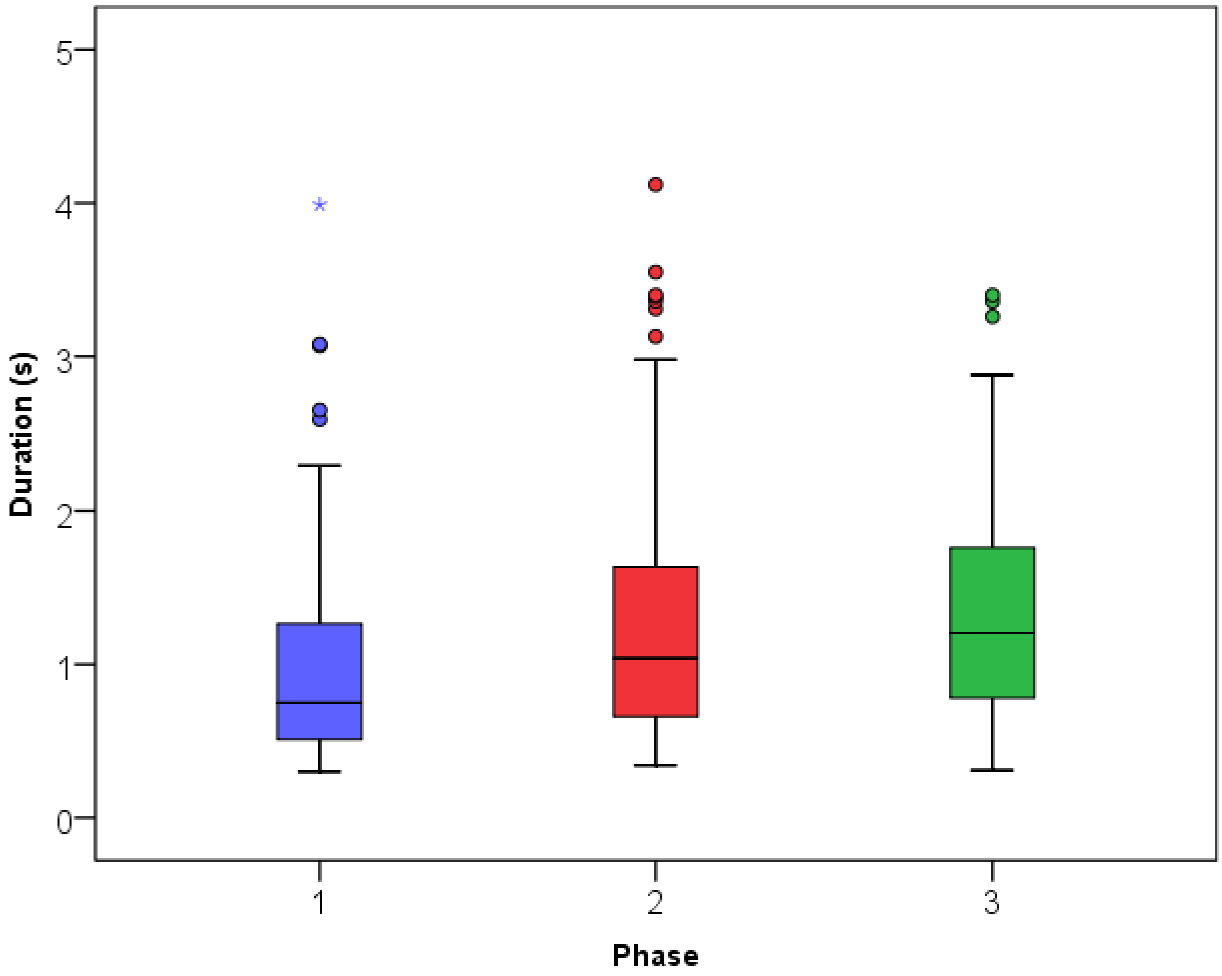

Figure 3.8. Median durations of vocal segments produced by child AE across the three phases of data collection.

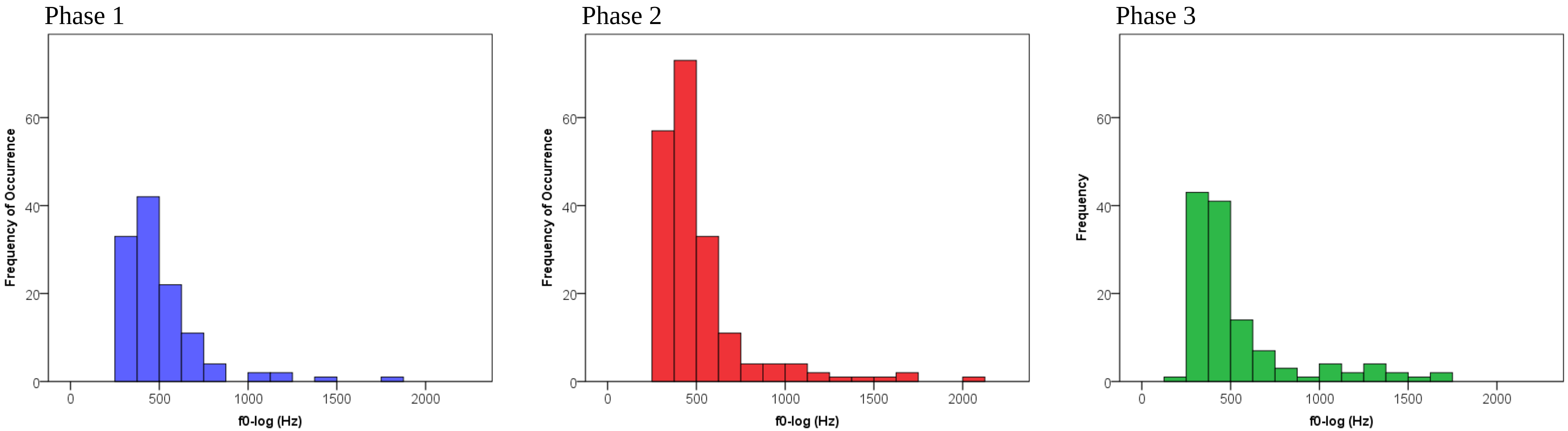

Figure 3.9. Distribution of vocalisation f0 for child AE during Phases 1-3 plotted according to a logarithmic scale. Each histogram represents a bin length of 25 Hz.

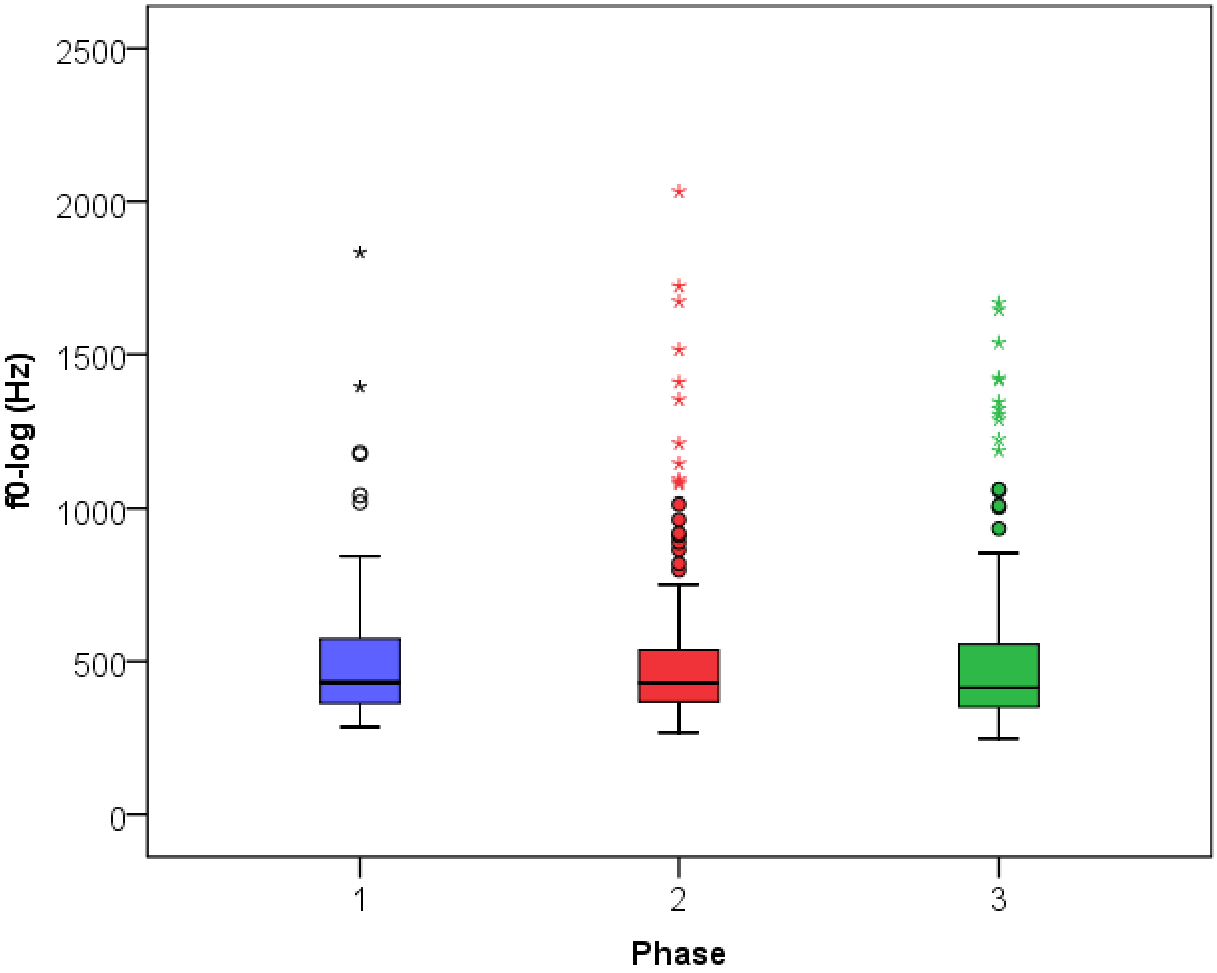

Figure 3.10. Median f0 of vocalisations produced by child AE across the three phases of data collection.

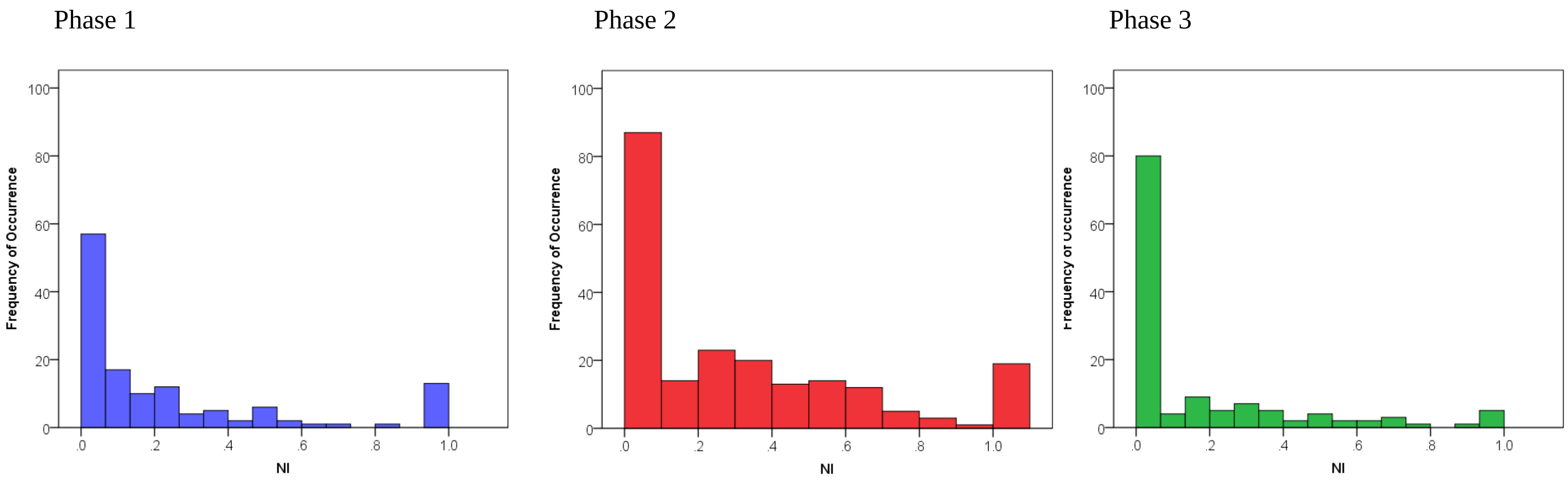

Figure 3.11. Distribution of NI values for child AE during Phases 1-3 . Each histogram represents a bin length of 0.1.

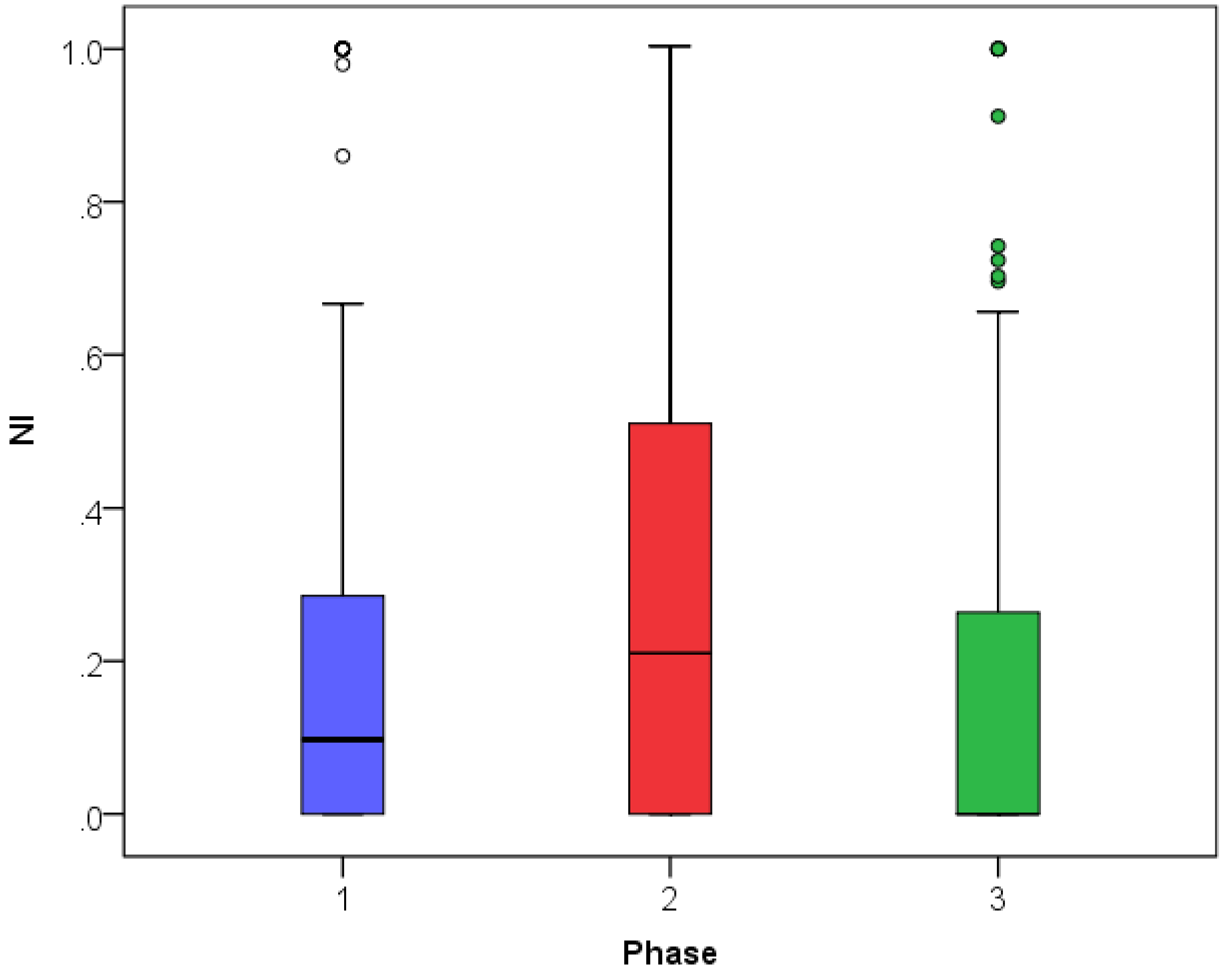

Figure 3.12. Median NI of vocalisations produced by child AE across the three phases of data collection

4 Summary of Results

1. The mean duration of vocal segments was longer for both children after CI switch-on as opposed to before switch-on (with no amplification/only HA use). The duration of vocal segments increased in range for both children when wearing hearing aids compared to no amplification, but only increased further after CI switch-on for AD. Variation in vocal segment duration decreased after CI switch-on for both children.

2. The mean f0 of vocal segments increased for both children after CI switch-on, when compared to no amplification. AD showed greater variability in the mean f0 of vocal segments between no amplification and HA/CI wear, and also displayed an increased range of f0 values after initial amplification provision with hearing aids (no change between HA and CI switch-on), than compared to AE. Variation in f0 increased after CI switch-on for both children.

3. The two children demonstrated opposite patterns in regard to the NI of vocal segments after CI switch-on. The average NI of vocal segments for AD increased with greater amplification provision. Conversely, the average NI of AE's vocal segments decreased with greater amplification provision. Variation in NI after CI switch-on decreased for AD and increased for AE.

Table 3

Summary of Results

AD	Duration (s)			f0 (Hz)			NI		
	Mean (SD)	CV (%)	Median	Mean (SD)	CV (%)	Median	Mean (SD)	CV (%)	Median
Phase 1 (nil)	1.09 (0.65)	60	0.91	471 (309)	66	360	0.25 (0.29)	116	0.17
Phase 2 (HA)	1.29 (0.75)	58	1.29	698 (531)	76	423	0.31 (0.30)	97	0.24
Phase 3 (CI+HA)	1.71 (0.91)	53	1.59	619 (455)	74	433	0.36 (0.31)	86	0.30
AE	**Duration (s)**			**f0 (Hz)**			**NI**		
	Mean (SD)	CV (%)	Median	Mean (SD)	CV (%)	Median	Mean (SD)	CV (%)	Median
Phase 1 (HA)	0.95 (0.64)	67	0.75	504 (226)	45	431	0.23 (0.31)	135	0.10
Phase 2 (nil)	1.25 (0.76)	61	1.04	512 (265)	52	429	0.30 (0.33)	110	0.21
Phase 3 (CI)	1.34 (0.70)	52	1.21	537 (316)	59	413	0.16 (0.27)	169	0.00

5 Discussion

The purpose of this study was to investigate the changes to acoustic features of vocalisations before, during, and after cochlear implantation in two congenitally deaf toddlers. The two children's spontaneous comfort vocalisations were recorded approximately every 4 days for 3-4 weeks before cochlear implantation, after implantation and before CI switch-on, and after CI switch-on. Measurements of duration, f0, and NI were taken from these vocal segments. A research question was posed: how do the acoustic features of the vocalisations of two congenitally deaf toddlers change longitudinally pre- and post-cochlear implantation? From a review of the literature, four hypotheses were proposed:

1. H_1: Duration of vocalisations decreases upon CI activation

   H_0: Duration of vocalisations do not decrease upon CI activation

2. H_1: Vocalisation f0 decreases upon CI activation

   H_0: Vocalisation f0 does not decrease upon CI activation

3. H_1: Noise Index decreases upon CI activation

   H_0: Noise Index does not decrease upon CI activation

4. H_1: The pattern of variation of these acoustic parameters will be at a stable baseline prior to CI and increase immediately post-switch on.

   H_0: The patterns of variation do not change upon CI activation

The following discussion investigates the acoustic changes to each child's vocal segments and gives possible explanations for these using the established concept of auditory feedback. First, the effects of cochlear implantation on vocal segment duration will be examined, followed by f0 and NI respectively. Next, the limitations of the current study will be addressed, as well as clinical implications and possible directions for future research.

5.1 Duration

The results illustrate that in both cases examined for this thesis, the duration of spontaneous comfort vocal segments increased for the period after CI switch-on (Phase 3) as opposed to during the periods of hearing aid use (Phase 1) or no amplification (Phase2). From these results, the null hypothesis cannot be rejected as neither child showed a decrease in duration. Both children displayed lower coefficients of variation in Phase 3 when compared to the other two Phases, and so the null hypothesis that variation will not increase also cannot be rejected.

These findings are of particular interest when compared to the body of acoustic literature on infant and toddler vocalisations. An early investigation into the patterns of comfort speech development in normal-hearing children of a similar age (11-25 months old) found that voiced segment durations decreased as age increased, from a mean of 497ms in 11-13 month olds to 321ms in 23-25 month olds (Robb & Saxman, 1985). Earlier studies exploring word and syllable durations in older normal hearing children’s speech (2-4 years old) also found decreases across the age ranges of subjects (Kubaska & Keating, 1981). In contrast, Kent and Murray (1982) described the duration of comfort utterances of 21 normal hearing 3-, 6-, and 9-month olds in terms of their distribution (visualised in histograms). They found that most utterances were less than 400ms across these age ranges, but distributions became more positively skewed towards larger durations as age increased. No descriptive statistics on duration were reported in this study. Rothganger (2003) reported an increase in the duration of babbles of 15 normal hearing infants over the first year of life. More recently, Fuamenya et al. (2015) reported a significant increase in the duration of spontaneous cries in younger normal hearing infants over the first three months of life. In this case, mean cry duration increased from 1.22s in month 1 to 1.64s in month 2 and measured 1.62s in month 3. Collectively, these studies show a pattern of speech/cry duration increasing in the first year of life, with a subsequent duration decrease thereafter for normal hearing children.

The findings related to vocalisation duration for hearing impaired infants and children are less clear, as well as less extensively studied. Several studies were published in the 1990s by a group of Dutch researchers who carried out a longitudinal investigation into the vocalisations of deaf vs normal hearing children (Clement & Koopmans-van Beinum, 1995, 1999; Clement et al., 1996; Van Den Dikkenberg-Pot & Koopmans-van Beinum, 1997; van der Stelt, Pols, & Wempe, 2003). In these articles, 6 profoundly hearing impaired (HI) infants and 6 matched normal hearing (NH) infants were followed over the first two years of life, between the ages of 2-18 months. Spontaneous comfort vocalisations were collected every 2 weeks, and the duration of 50 random vocal segments from each session were measured. The investigation found the mean vocalisation duration over the age range of 2.5-8.5 months was not significantly different between the two groups, although the HI infant's vocal segments were in general longer than the NH children. A significant increase in duration occurred for the NH infants around 3.5 months of age that was not found for HI group. This observation was accounted for by both the changes in anatomical ribcage structure as well as the increased ability to control subglottal air pressure via neural development of the speech motor system. The lung volume of younger NH infants was too small to produce vocalisations of this length, whilst the HI infants did not have access to the auditory feedback required to develop vocal (i.e. air pressure) control. The authors noted that this difference may support the theory of a critical or sensitive period for neuromuscular maturation of the vocal tract (Clement et al., 1996). A significant difference in duration was found between the groups for the age range of 10.5-12.5 months to 14.5-16.5 months of age. In summary, the HI children produced longer vocalisations on average when compared to their NH peers from 10.5 months of age until the end of the investigation at 17.5 months. Two of the HI children showed a substantial increase in vocal segment duration with age over this period, while three others displayed a decrease over time. The authors postulate that this difference is attributed to the difference in speech production occurring at this time – a period in which the normal hearing children begin to say their first word (characterised by shorter duration) and the hearing impaired children continue to either produce long vocalisations of simple sounds, or primitive babble.

Interestingly, a recent presentation by Binos (2017) investigated the duration of isolated vowels for two congenitally deaf infants in their second year of life for six months following cochlear implantation. The researcher found that the two deaf infants produced significantly longer vocalisations after implantation than their normal hearing peers.

In regards to the current study, the findings that AD and AE both increased their vocal segment duration after cochlear implantation is somewhat in agreement with the above literature. The evidence on vocal duration for hearing impaired children of similar ages to AD and AE indicate that non-implanted deaf children produce longer vocalisations than normal hearing peers, a trend that is similar in recently implanted children. Correspondingly, AD and AE's vocal segments were longer than their normal hearing peers both before and after implantation. The detail illustrated in this study, and not by previous investigations, is the immediate segment duration increase after CI switch-on. Several explanations could be given to this trend; which all in essence can be attributed back to the restoration of sufficient auditory feedback after activation of the CI.

The first explanation hinges on the deficit model of the speech of these two children. Before cochlear implantation, AD and AE's speech development is estimated to be around that of a normal-hearing three month old infant. It therefore could be argued that their speech and vocal development is markedly delayed to such an extent that they could not be expected to show the same durational patterns as previously reported for normal hearing children of the same age. Interestingly, the duration of vocal segments exhibited by AD and AE show similarities to the patterns found in normal hearing 3.5 month old infants of the longitudinal investigation by Clement and Koopmans-van Beinum (1995). It is possible that AD and AE's rapid duration increase is due to the establishment of advanced conscious control of subglottal pressure and laryngeal muscles, as is postulated in this past work. The duration results also display similar patterns to those presented by Kent and Murray (1982) for 3-9 month old NH infants, whereby comparable modal peaks are seen in very short duration segments, with an increase of skewing to the right over time. This is further evidence that the increase in duration could be explained by the delayed phase of speech development AD and AE owing to their largely unresolved profound hearing losses, which is then accelerated into subsequent stages with the activation of their CIs.

A second explanation could be that the results are attributed to the strengthened intentionality of vocalisations made by these two children, once their access to auditory feedback was expanded by the CI switch-on. In theory, CIs provide AD and AE with the chance to experience a vastly wider range of sounds (and therefore auditory feedback) than other forms of amplification such as hearing aids could provide. Because AD and AE were no longer infants, their cognitive ability to experiment with sounds after gaining this new form of feedback from speech could be thought of as relatively more advanced than the usual progression of speech development by normal hearing children. This assumption, in turn with previously established theories on the mechanisms of speech development can be used to illustrate an explanation for the duration increase. As described by Guenther (2006), speech production is a function under the neural control of three main subsystems: auditory feedback, somatosensory feedback, and feedforward. Until the switch-on of their CI's the vocal segments produced by AD and AE can be assumed to have relied heavily on somatosensory feedback, as their auditory feedback would have been limited and the feedforward system does not develop extensively until after language-specific sounds are learned (Tourville & Guenther, 2011; Tourville et al., 2008). After the CI was switched on, AD and AE were able to use their developed somatosensory feedback mechanisms to intentionally 'play with' and investigate the new auditory feedback. This explanation is in accordance with findings by Fagan (2015) who described the commencement of 'vocal exploration' by way of repetitive babbling in the first 2-3 months following infant cochlear implantation. Fagan proposes that these vocal repetitions are intentionally produced to create auditory feedback, due to the infants' motivation to explore this new element. In normal hearing children, this is seen around the age of 7-8 months but is either delayed or absent from hearing impaired children (until the provision of sufficient amplification). Although not investigated in either the current or above-mentioned research, it is reasonable to assume that repetitive babble is reflective of longer segment durations than the short vocalisations produced by AD and AE before CI switch-on. Therefore, the duration increase measured in this investigation could be justified by the same reasons proposed by Fagan. The durational characteristics of AD and AE's vocalisations reflected the initiation of purposeful, intentional, and self-generated motivation to vocalise once auditory feedback was accessed.

If either of these theories were held to be accurate, it would be likely that AD and AE would show vocal segment duration decreases as their speech development continued to progress, just as is seen in normal hearing infants. In accordance with this, a past CI on/off study of the speech of children demonstrated that word durations increased when the CI was switched off (Poissant et al., 2006).

5.2 Fundamental frequency

The f0 is inherently related to laryngeal tone, and therefore an individual's laryngeal control of the vocal folds (Fant, 1971). Before cochlear implantation, AD and AE demonstrated abnormally high mean f0 values of 471Hz and 504Hz respectively. These are both higher than any of the noncry f0 data of normal hearing infants reviewed by Iyer and Oller (2008), of which the highest f0 was 450Hz. Both AD and AE demonstrated an increase in mean f0 in Phase 3 (post-CI), an effect that is uncommon in the literature. The proposed null hypothesis that f0 will not decrease after CI activation can therefore not be rejected from these results. Likewise, the variation in mean f0 was expected to increase in Phase 3, as the children's voices normalised to a new baseline level. However both AD and AE showed a decrease in variation in Phase 3. Therefore the proposed null hypothesis that mean f0 variation will not increase is also unable to be rejected. Although some papers show a non-significant decrease in paediatric f0 post-CI (Hocevar-Boltezar et al., 2005), some display significant increase (Joy et al., 2017; Monini et al., 1997), and others still show no change after cochlear implantation (Campisi et al., 2002; Hocevar-Boltezar et al., 2006). Of course, other factors such as the f0 pre-CI switch on, age of the children followed, and the length of time between follow-up measurements may also play a part in these varied results.

Again, one possible explanation for the results seen here is an increase in the intentionality of AD and AE's vocalisations post-CI switch-on. Once they are able to properly hear their own voice, it would be reasonable to expect the children will go through a stage of vocal exploration and play, in order to learn more about the sounds they are producing. This could be related to either the pure acquisition of audition through CIs, and/or the rapid progression into successive stages of speech development once their levels of auditory feedback are sufficiently increased. The main point of difference between these two theories is the presence or absence of intentionality – are AD and AE consciously producing more vocal segments at a higher f0, or is this an unconscious behaviour?

Conscious, motivated vocal play after infant CI activation has been recently implicated in investigations by Fagan (2014, 2015). These studies evaluated infants who were implanted at a mean age of 12.9 months old, and used measures such as frequency of occurrence of vocalisations as well as the quality and type of vocalisations produced. The findings suggest that auditory feedback is necessary to increase the quantity and variability of pre-babble infant phonations, which in turn are necessary for the timely development of canonical babble. Although these studies did not include the measurement of f0, the notions and implications can be applied to the current cases of AD and AE. Because neither of these infants were regular, long-term wearers of hearing aids prior to these recording stages, the large majority of their speech feedback will have been through the somatosensory subsystems. Their abnormally high f0 prior to CI is therefore very likely attributed to lack of laryngeal control, as seen in previous works (Clement & Koopmans-van Beinum, 1995; Iyer & Oller, 2008). Then, once the CI is switched on, they are suddenly given access to a wide range of new sensations which gives them the ability to compare their vocal productions to an entirely new type of feedback (auditory) – leading to new motivation to play with their laryngeal tension. Several studies have noted that post-CI f0 control takes longer to normalise than other parameters, and so perhaps the short-term basis of this analysis did not allow for a converse reduction in habitual f0 which could have prevented the observation of the exploration phase in other papers (Hocevar-Boltezar et al., 2005; Joy et al., 2017; Wang et al., 2017). It’s worthy to note that by the second year of life, normal hearing infants are generally beginning to vocalise their first words, and so infants of this age most certainly have the cognitive development necessary to intentionally modify their voice and create intentional vocalisations.

On the other hand, Kuhl and Meltzoff (1996, p. 1) describe the expansion stage of vocal development as “characterized by the occurrence of clear vowels that are fully resonant and a wide variety of new sounds such as yells, screams, whispers, and raspberries”. Auditory analysis of the pre-CI recordings of AE and AD indicated that they were both at the speech developmental stage of normal-hearing three month olds. Both children were already producing some of these sounds which rely heavily on kinaesthetic and proprioceptive feedback, such as raspberries and pulse register phonation. However other sounds such as screams would not have provided them with the same amount of sensations before CI switch-on. It could therefore be reasonably argued that the increase in f0 is not a solely intentional response to auditory feedback via CIs, but also a natural step in the development of the speech and language of these children. Again, laryngeal control is likely to take longer to develop than this study is able to assess with the given recordings, as evidenced by the lack of change to the modal peaks shown in the f0 histograms of Figures 3.3 and 3.9. This indicates that the habitual f0 of AD and AE’s voices has likely not changed, but the increase in the number of high frequency vocalisations has resulted in a change to the overall mean f0.

It is likely that both of these explanations are correct to some degree. A progression through speech development stages is naturally expected before AD and AE begin to produce words, and they are likely reaching these stages with a higher cognitive ability than most normal hearing infants. This could also attribute to the larger increase in vocal f0 of AD when compared to AE, as AE was already in a slightly more advanced stage of vocal development and may have had less need to undertake a large period of expansion and vocal play. Perhaps the fact that this pattern is not commonly seen elsewhere in the literature is due to the ages of

AD and AE; other studies of CI effects have generally measured preschool-aged children who may be old enough to somewhat bypass this stage of vocal play.

5.3 Noise index

The amount of noise contained in each child's vocalisations was estimated using the NI measure. The two children were observed to differ in regard to this particular measure. For example, once AD was supplied with greater provision of amplification (CI switch-on), the mean NI of his vocal segments increased. Likewise, the total percentage of vocalisations containing noise also increased after CI switch-on for AD. On the contrary, as AE was provided with greater amplification the mean NI of her vocal segments decreased, as did her total percentage of vocal segments containing noise decreased as well. Therefore, the null hypothesis that NI will decrease with CI activation can be rejected for the results of AE, but not for AD. Likewise, the variation of NI was expected to increase in Phase 3. This occurred for AE, but AD showed a decrease in variation. The null hypothesis that variation will not increase after implant switch-on can therefore again be rejected for AE but not for AD.

Fuamenya et al. (2015) examined infant cries and found NI to decrease across the first three months of life from 0.20 for the first month of life, 0.18 for the second and 0.08 for the third. The authors attributed the occurrence of noise to the structure of the infant vocal folds, which are not mature until around 11 months old and show rapid structural changes in the first two months of life. This is thought to lead to a tendency for high subglottal pressures, resulting in noisy cries. Direct comparison of the results of Fuamenya et al. (2015) to those of the present children is not possible because these authors examined the cries of normally hearing infants. Nonetheless it is worthy to note that after CI switch-on the mean NI of AD was considerably higher than these values for infant cries, whilst the mean NI of AE was similar to them.

A related measure of vocal noise is the ‘noise to harmonic ratio’ (NHR), which has been reported in several articles as an outcome measure of the vocalisations of hearing impaired adults and children, to compare pre- and post-cochlear implantation or to compare the vocal characteristics of different groups of subjects. Norms have not yet been established for NHR for infant/child comfort vocalisations, however adult norms for NHR have been established by way of a threshold of pathology – commonly defined as 0.19 (Deliyski, 1993). Two notable papers by Hocevar-Boltezar and colleagues have used NHR to compare the vocal qualities of hearing impaired children before and after cochlear implantation. The first explored acoustic features of children who were implanted before and after 4 years of age. The researchers found that before cochlear implantation, hearing impaired children under the age of four years had a significantly higher mean NHR (0.23) than hearing impaired children over the age of 4 years (0.11) (Hocevar-Boltezar et al., 2005). After cochlear implantation the NHR of the younger group showed a decrease by 12 months post- CI, a difference which was significant by 24 months post-CI. The children implanted at an age older than 4 years did not show a change in NHR; and by 24 months onward both groups displayed essentially equivalent mean NHR values (both 0.11). The authors postulated that the older group’s lack of improvement in this sense was due to already developed neuromuscular control of the vocal system, and concluded that children implanted before 4 years old showed greater and more rapid improvement of vocal control.

The second NHR study examined the acoustic outcomes of CIs in prelingually deafened children vs. postlingually deafened adults (Hocevar-Boltezar et al., 2006), The results showed that the NHR for the children (mean age 5.89 years) decreased from 0.17 pre-CI to 0.14 post-CI, but the change was not significant. The postlingually deaf adults did not show a change in mean NHR (0.12 pre- and post-CI). The authors interpreted the NHR of the children to be within normal values both before and after CI, although they did note the improvement after implantation.

As described above, most literature considers high noise content to be a pathologic indicator for vocalisations and speech. Abnormally high NI or NHR values are therefore expected to decrease after cochlear implantation. It is also expected that typical, non-pathologic speech will contain some aperiodicity (Deliyski, 1993), particularly in infants (Fuamenya et al., 2015), and that normal development of infant speech involves a reduction in aperiodic components as the physiological structure and function vocal tract develops into maturity.

It is important to note that the two children in this study, AD and AE, were respectively 13 months and 18 months of age around the time of cochlear implantation. These two children were therefore considerably older than the infants investigated by Fuamenya et al. (2015) but still much younger than the children in Hocevar-Boltezar et al. (2005) and Hocevar-Boltezar et al. (2006). It can be expected that the anatomical changes to the vocal tract observed around the 11th month of life and implicated in Fuamenya and colleagues' evaluation have already occurred, although AD and AE exhibited the speech and language development of a normal three month old at the time of cochlear implantation.

From these observations, it can be deduced that the pattern of mean NI for AE follows the expected pattern for cochlear implanted infants. The NI of AE's Phase 2 (no amplification) was higher than Phase 1 with provision of bilateral hearing aids, which was again higher than Phase 3 after CI switch-on. Therefore, the more amplification AE was provided with, the less noisy her vocalisations became. These results suggest that AE benefitted from the increased access to sound and her overall vocal control improved once she was able to utilise the newly acquired auditory feedback to create more periodic (and acoustically pleasant) vocalisations.

Another explanation for the reduction in average NI for AE was simply a consequence of development, regardless of whether acoustic feedback was present or not. Yet the rapid manner in which AE's mean NI reduced when she was provided access to the auditory environment suggests that this change is likely not primarily due to anatomical restructuring of the vocal folds as in Fuamenya et al. (2015). Rather, the reduction in NI appears to be a consequence of the enhanced auditory feedback –already shown to promptly improve acoustic qualities of children's' speech (Poissant et al., 2006). The swift decrease in NI also suggests that her cognitive and learning abilities were already at a sufficient stage in order to process and moderate her own voice once she could hear it.

The NI results for AD were revealing of a different pattern of vocal development. The mean NI per vocal segment for AD increased as he was given more access to auditory signals – from 0.25 with no amplification, 0.31 with a unilateral hearing aid and 0.36 with the CI switched on. This pattern is not in agreement with existing literature and theories on aperiodic speech and effects of acoustic feedback, and so was somewhat of a surprising result.

One explanation for this relies on the pattern of NI results seen in the session-by-session representation Figure A3. In this figure it is evident the average vocal segment NI of recording sessions immediately following CI-switch on (days 402-412) were noticeably higher than those sessions several weeks after switch-on (from approximately day 412 onwards).Acoustic observations of AD's vocalisations suggest that his typical vocal profile includes a large amount of pulse register phonation, or 'vocal fry'. This may be because vocal fry is likely to create more kinaesthetic and proprioceptive feedback than harmonic vocalisations. As Yates (1963) and Guenther (2006) explained, the feedback from speech falls into two categories – auditory and somatosensory (Guenther, 2006; Yates, 1963). Somatosensory feedback can be further defined as kinaesthetic and proprioceptive information that arises from the afferent sensory nerves and muscles implicated in vocalisations. Because AD was deprived of the auditory aspect of speech feedback for a significant amount of time, his vocalisations developed with a notable proportion of vocal fry – the only feedback he was able to sense and therefore consciously moderate. It would then seem reasonable to conclude that AD used this pre-learned, pre-developed type of vocalisation to explore his new auditory environment once the cochlear implants were switched on. As Fagan (2014) described, CI activation leads to a rapid commencement of vocal play and exploration, similar to that seen in younger normal hearing infants (Stark, 1981). The session-by-session results (Figure A3) appear to support this suggestion – AD begins his auditory exploration by intentionally experimenting with the sounds he knows which culminates in higher NI values per recording session. As time progresses he begins to learn to control the vocal fry and produce vocalisations with a higher proportion of hamonicity, indicated in the drop in average NI for recording sessions from around day 415 onwards (Figure A3).

The conflicting NI results of AD and AE can be explained using one theory of acoustic feedback (Guenther, 2006). Although the current results do not cover the longer term effects of cochlear implantation on NI, the patterns of NI values seen in Phase 3 for AD suggest that both children may display reduced vocal NI values after a longer period of adaptation to the implants. Even before cochlear implantation, AE's speech development was more advanced than AD –auditory analysis of the vocal recordings showed she began to display the initial stages of canonical babble after a shorter period of implantation than AD. If this was the case, the present results may have been in agreement with past literature on the effects of cochlear implantation on speech aperiodicity if a longer post-CI period was examined.

5.4 Limitations

This study has limitations which necessitate careful interpretation and consideration of the results. First, the research was limited by the measures used. There are many acoustic features that can be used to evaluate speech, including (but not limited to) jitter, shimmer, formant frequencies, phonatory regimes, and phonetic transcription. As this study was measuring very simple preverbal vocalisations, the chosen acoustic measures were also basic features of voice (f0, duration, NI) that are often used to study preverbal infant vocalisations. Although these children were at a preverbal stage in their speech development, they were chronologically older and more cognitively developed than the studies of other individuals using these outcome measures. It is possible that the inclusion of other measures such as those listed above may have provided additional information about the immediate changes observed with the restoration of acoustic feedback via cochlear implants, which would have given the overall analysis increased depth and scope. Likewise the extension of measurements, particularly further into the post-switch-on stage, may have provided a more complete picture regarding the vocal changes occurring with the provision of cochlear implants.

Second, the techniques employed to measure the acoustic features were a limitation of the overall results. There is some debate regarding the most accurate methods to carry out acoustic examinations(Dejonckere et al., 2001) and this thesis applied both auditory and visual analyses to identify and measure the chosen outcomes. Assessing each vocal segment individually can improve the accuracy of measurements and identification of acoustic features by allowing the use of personal insight and decision-making – processes unable to be employed by way of automated software programmes. However this technique does introduce a large amount of subjectivity into the measurement process, a limitation when comparing the results to past or future studies. It is important to comprehensively define the measurement techniques and acoustic features to lessen ambiguity of the result. Similarly, the measurements in this research were carried out by an individual who was not especially experienced in acoustic analyses. Although training was provided, and oversight given by two skilled researchers, it is likely the analysis would have been afforded greater precision and accuracy if carried out by an individual with more expertise in these methods used.

Third, as mentioned in the above methodological chapter, the software used had inherent limitations to its ability to measure the chosen acoustic features – particularly in terms of f0. Careful observation was necessary to fit the PRAAT pitch line to the true f0 of each vocal segment, but this was difficult for the vocal segments with integrated aperiodic components, and large pitch shifts. Although some steps were taken to minimise the effect on the research, as detailed in the methods, the use of a more complex measurement programme may have allowed for greater measurement accuracy.

Finally, some large limitations exist in the generalisability of this research and results. This study was intended to be viewed as a case study of two congenitally deaf infants, and so the results found are difficult to extend and generalise to other situations and cases outside of these children. The results may hold more weight if the number of participants was larger, and if tests of statistical significance were carried out on the results. It is also not possible to rule out the influences of external factors that may have affected the results, particularly those previously established to affect the speech and language outcomes of hearing impaired children. Several socio-economic factors have been shown to improve these outcomes, such as amount of language use by parents and the mother's education levels (Yoshinaga-Itano et al., 2017). A more thorough investigation into AD and AE's lifestyle and home environment may have provided more justifications for both the changes observed, and the differences in results seen between these two children.

6 Clinical Implications and Future Directions

6.1 Clinical Implications

Current outcome measures of amplification fitting to young infants and children involve a range of objective and subjective techniques, from aided sound field testing to interviews and questionnaires completed by parents or caregivers. Just as aided sound field testing is currently interpreted as an objective effect (measuring the benefits) of amplification, further research could allow the measured changes to a child's speech to be used as an additional objective measure of hearing aid or CI outcomes. However this notion would require some effect(s) of restored auditory feedback on infant speech to be consistent between children.

Overall, this thesis has succeeded in illustrating the effects of restored auditory feedback on the vocal profiles of two prelingual children. As this case study only follows the development of two children, its wider clinical implications are limited. It is clear from the results (as well as past literature) that although deaf infants and children are expected to show particular vocal traits upon restoration of auditory feedback, there is not currently 'one size fits all', nor one finding which is always consistent. The present case studies on children AD and AE show several changes once CI switch on occurs, some of which are in accordance with the literature but several which are not; as well as some contrasting changes between the two children themselves. With further research on the effects of auditory feedback in infant development (particularly when accessed through CIs), acoustic parameters such as vocal duration, f0 or noise index could be used as a complimentary tool alongside current paediatric CI objective verification measures. This would require investigations of a larger scale, following more children of similar ages over a longer period with frequent recording sessions. Greater consensuses between researchers in regard to measurement procedures would also ease the combining of multiple papers' findings.

At present, the findings of this thesis are too inconsistent (both between the subjects and compared to other research) to hold strong clinical application. Rather, this thesis should be taken as evidence that even if implanted children clinically demonstrate unexpected vocal changes immediately following CI switch on, it does not necessarily indicate undesirable results. Perhaps the sole presence of observable changes (particularly in the duration and NI of vocalisations) is a positive indication of restored auditory feedback, no matter the direction of change. Further vocal data obtained from these children indicates that they went on to rapidly produce canonical babbles, with AE saying her first protowords within a few months of CI activation. It is highly probable that as their speech development progresses, the voices of AD and AE would undergo further normalisation.

6.2 Future Directions for Research

As this study involved the analysis of only two infants, future studies should of course involve a larger number of infants. One possible future direction would be to investigate the acoustic parameters of duration, f0 and NI with the same frequency of sessions (i.e. weekly recordings) but over a longer time frame. This would give a more detailed picture as to the effects of auditory feedback restoration on infant vocalisations, as the current results imply that changes are still occurring at the end of Phase 3. As previously addressed, it is very likely that the time period of Phase 3 was not long enough to illustrate normalisation of vocal parameters without the effects of vocal play, however this would need to be further analysed to be definitely concluded.

Furthermore, the concept of infant vocal exploration and play due to auditory feedback restoration has been fundamentally implicated in the current results but is relatively unexplored in research – particularly involving the use of the physical measures of acoustic features. Although many studies have looked at the behaviours and patterns of vocal play, as Fagan (2011, 2015) reviews, these do not involve the measurement of acoustic features as this thesis has explored. Future studies could continue to investigate whether these short term changes to vocalisations after cochlear implantation are consistent between deaf infants, or whether this is just as inconsistent as the many published longer term acoustic analyses.

Another future direction for research could be a more in depth investigation into the concept of intentionality in vocalisations of CI infants. AD and AE are both relatively old for infant CI candidates, as most congenitally deaf children are implanted around the age of 12 months or earlier. Therefore it would be interesting to investigate whether younger CI recipients have the same cognitive ability to generate this period of exploration, or whether this is unique to older deaf infants. Further investigation of this concept could allow for greater clinical implications of the vocal effects of infant CI – if most CI infants display these further deviations from normal acoustic values after switch-on, the effect could be used to help validate CI fittings and prescriptions.

7 Summary and Conclusions

In summary, this thesis did not succeed in rejecting the null hypotheses proposed for the effects of cochlear implantation on the vocal segment duration and f0 of AD and AE. The null hypotheses proposed for the effects of cochlear implantation on NI were rejected for AE but not for AD.

As previously described, the proposed hypotheses were based on literature of both the development of normal-hearing infants as well that of un-implanted deaf infants and deaf infants who undergo CI rehabilitation. Findings of the vocal development of normal hearing children are relatively consistent in previous research, with general decreases in duration, f0 and NI found over time. Likewise, although there is slightly less reliability for the acoustic features of un-implanted deaf infant voice, most exhibit increased vocal durations, f0 and higher Noise Indices. With that in mind, a major feature of investigations into CI effects on infant voice is the large degree of discrepancies in results despite the fact that restoration of auditory feedback via CIs is expected to support the normalisation of vocal acoustic parameters. For this reason, most infant CI vocal studies formulate their hypotheses on the expected vocal changes if normalisation was to occur after implantation, with the knowledge that deviations from these changes are commonly found.

The same idea was used to formulate the hypotheses of this thesis. Therefore although the null hypotheses were largely not rejected here, it does not necessarily indicate that the findings are inconsistent with previous research. The non-rejection of the nulls may be due to the very short-term nature of the investigation, which has allowed events such as increased motivation to vocalise and the commencement of vocal exploration and play to be observed in the results. It is likely that with further CI use, the acoustic features of AD and AE's voices will slowly normalise to be closer to the norms of NH children as their speech and language development also progresses to catch up with their peers.

These findings support ideas upheld by other researchers, such as Guenther (2006), Tourville and Guenther (2011), and Fagan (2014, 2015). Tourville and Guenther illustrated the importance of auditory feedback in the development of speech via the DIVA model, particularly regarding the advent of babbling. Auditory information is crucial to establishing strong and accurate neural pathways in areas of the brain implicated in vocal control, and this significance is supported by other models of speech production as well (Larson et al., 2008). Fagan investigated the relationship between restored auditory feedback and vocal development in CI infants – namely that CIs give sufficient auditory feedback to induce motivation and vocal exploration which lead to the commencement of the babbling stage. While these researchers have explored different aspects of speech production – Tourville and Guenther's neuroanatomy and neurophysiology studies versus Fagan's investigations of infant vocal behaviour – they both highlight the need for auditory feedback in vocal exploration and babbling, leading to speech development. Likewise, although this thesis focuses on different parameters again (in this case the acoustic measures of duration, f0 and NI), the same consequences of CI switch-on are observed to affect the measures.

All three parameters of duration, f0 and NI appear to be influenced by this vocal exploration, which may have overshadowed the expected vocal normalisation effects. This idea is supported by consideration of the session-by-session measures. In general, the later recording sessions of AD and AE in Phase 3 show duration, f0 and NI values which appear to be normalising (see Appendices A and B) in normally-expected directions. This may also be why the variation of almost all measures (except for NI of AE) decreased in Phase 3 – perhaps a period of increased variation after CI switch-on was too short to be seen in the results, but the period of vocal exploration is long enough to have an effect on the measures noted in these time frames.

To conclude, it is clear that cochlear implantation markedly aids the auditory feedback accessed by deaf infants. However the expected vocal normalisations were not observed here in the short time period covered – conversely, both AD and AE exhibited vocal features that were further deviated from norms in the time period after CI switch-on. The investigation of these two children demonstrates the unexpected results often found in vocal studies of rehabilitated deaf infants, which may be a result of intentional vocal play overshadowing any initial normalisation of acoustic features. Far from indicating a long term increase in vocal abnormality, the changes here imply that initial CI switch-on gives deaf infants the ability and desire to explore auditory feedback using their own voice, which in turn may allow their neurological speech development pathways to develop and strengthen the control of this system. Further investigation is needed to conclude that these acoustic parameters do indeed normalise in the long-term, but from the results indicated here, the access of auditory feedback via CI for AD and AE appears to be sufficient to enabling the development of babble and consequently speech.

8 References

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Appendix A

Acoustic Parameters of Child AD's Vocalisations per Recording Session

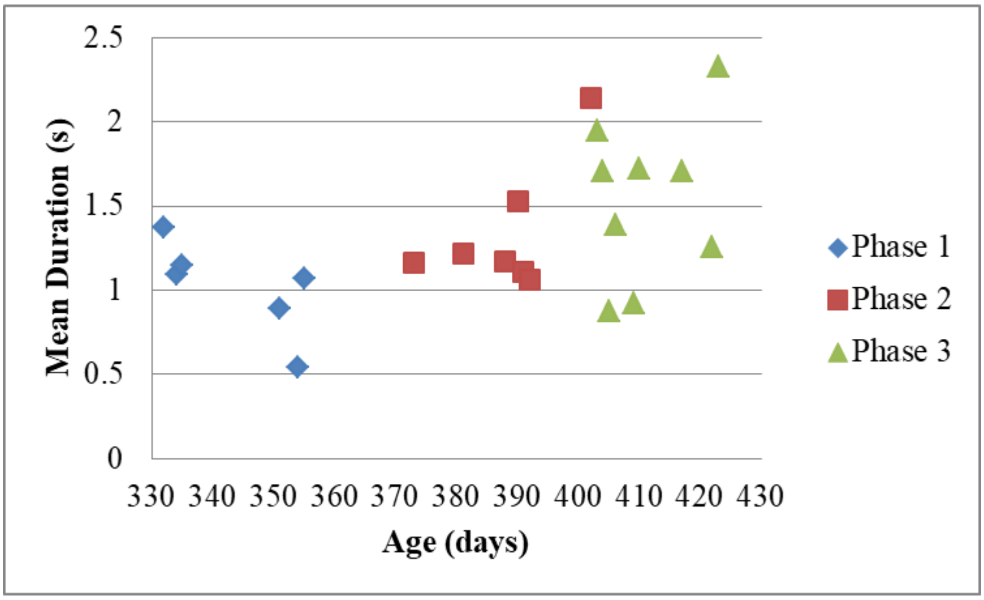

Figure A1: Mean vocal segment duration per recording session of Child AD. Sessions are recorded by age of AD in days.

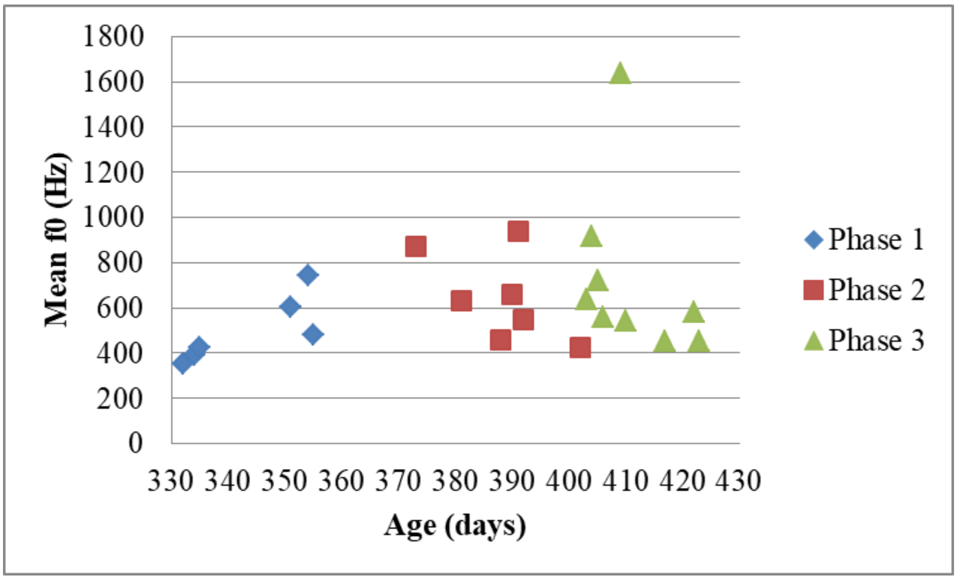

Figure A2: Mean vocal segment f0 per recording session of Child AD. Sessions are recorded by age of AD in days.

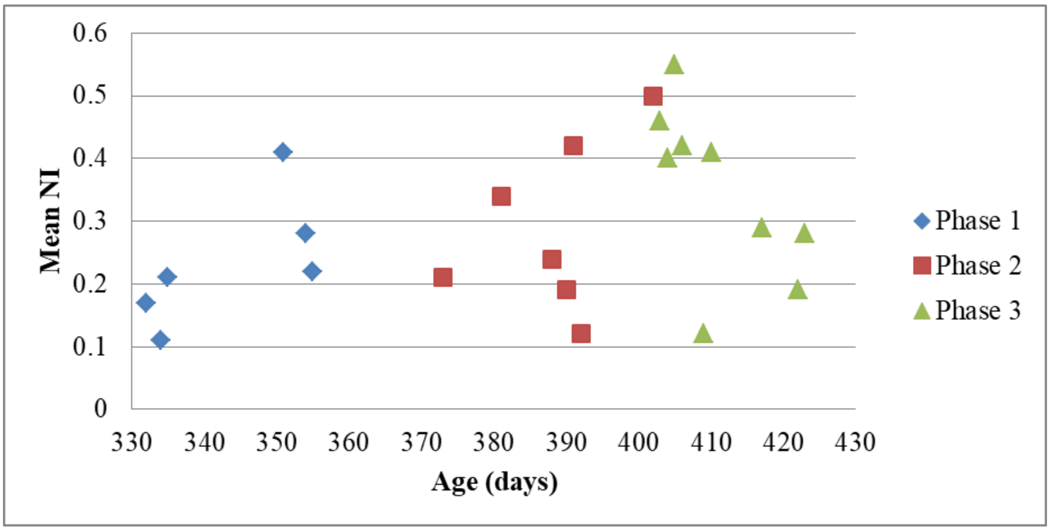

Figure A3: Mean vocal segment NI per recording session of Child AD. Sessions are recorded by age of AD in days.

Appendix B

Acoustic Parameters of Child AE's Vocalisations per Recording Session

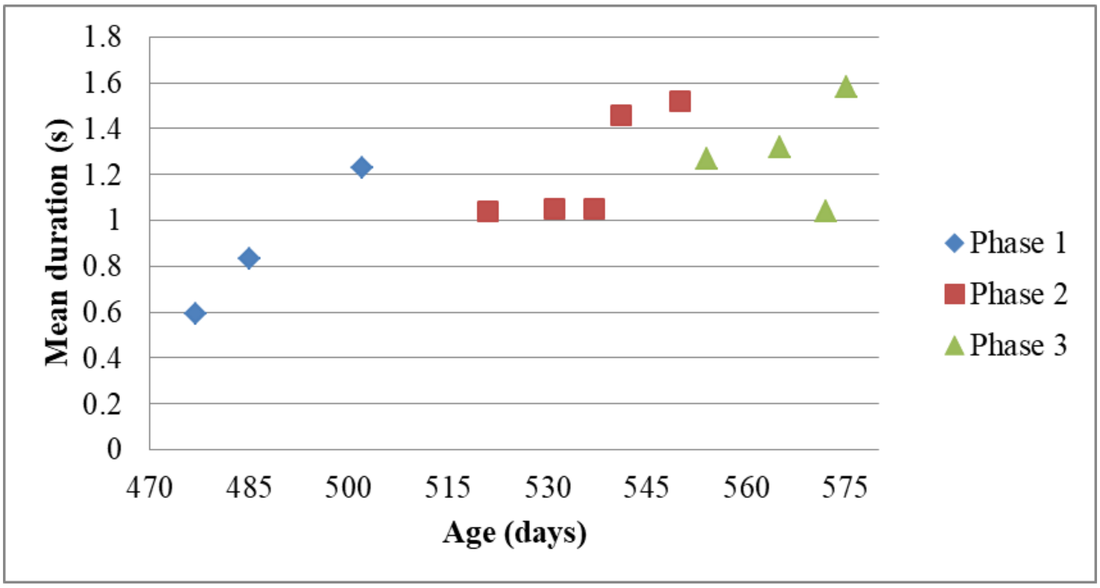

Figure B1: Mean vocal segment duration per recording session for Child AE. Sessions are recorded by age of AE in days.

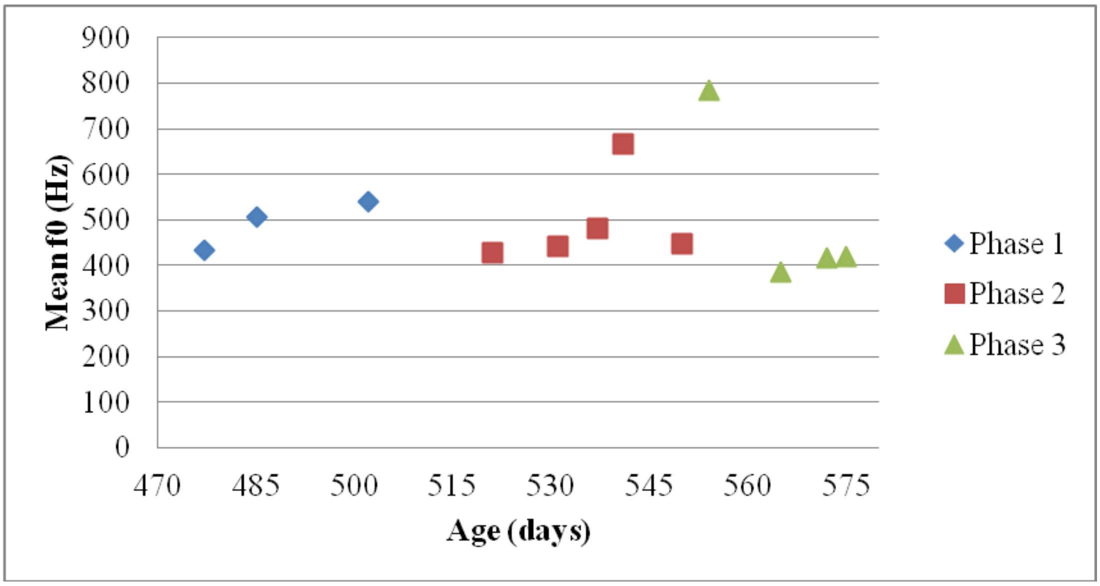

Figure B2: Mean vocal segment f0 per recording session for Child AE. Sessions are recorded by age of AE in days.

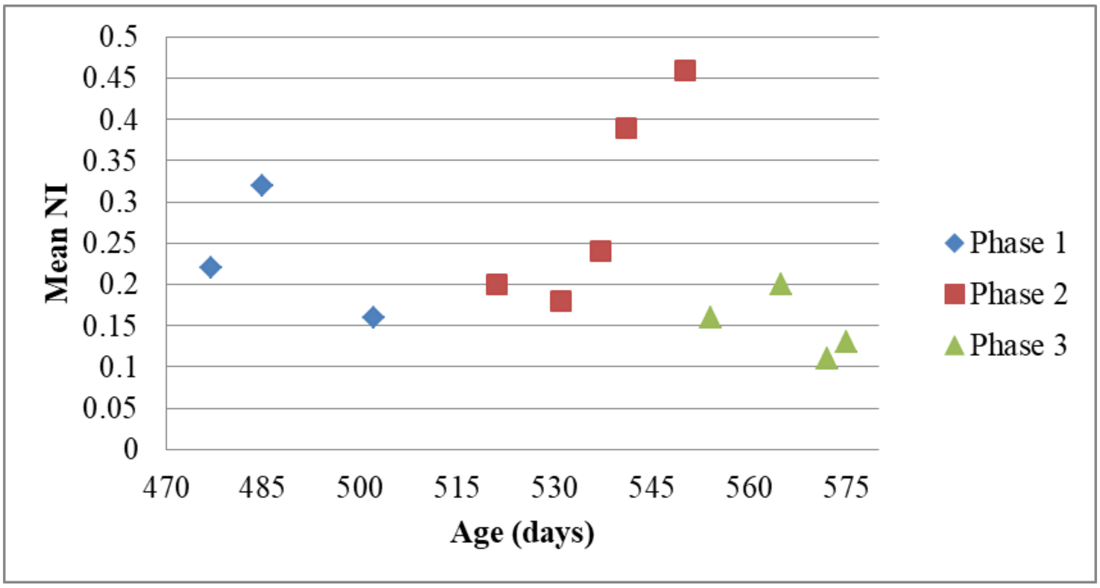

Figure B3: Mean vocal segment NI per recording session for Child AE. Sessions are recorded by age of AE in days.